Geophysical Monograph Number 2

Geophysics and the IGY

Proceedings of the Symposium at the Opening of the International Geophysical Year

Conducted by the

United States National Committee for
the International Geophysical Year
National Academy of Sciences
Washington, D. C.
June 28-29, 1957

Edited by

Hugh Odishaw and Stanley Ruttenberg

Geophysical Monograph Series
Waldo E. Smith, Managing Editor

AMERICAN GEOPHYSICAL UNION
OF THE
NATIONAL ACADEMY OF SCIENCES—
NATIONAL RESEARCH COUNCIL
Publication No. 590
1958

Geophysical Monograph No. 2
GEOPHYSICS AND THE IGY

1515 MASSACHUSETTS AVENUE, N.W.
WASHINGTON 5, D. C.

Library of Congress Catalog Card No. 58-60035

PRINTED BY THE LORD BALTIMORE PRESS, INC.
BALTIMORE, MARYLAND

Table of Contents

Preface .... Joseph Kaplan v

UPPER ATMOSPHERIC PHYSICS

Solar Terrestrial Relationships .... Walter O. Roberts 1
The High Atmosphere .... N. C. Gerson 6
Instrumentation for Global Observation of the Sun during the IGY .... John W. Evans 21
Whistler Studies at Dartmouth .... Millett G. Morgan 31
Whistlers and Very Low Frequency Emissions .... R. A. Helliwell 35
Probing the Ionosphere .... A. H. Shapley and Ralph J. Slutz 45
Upper Atmospheric Winds, Absorption and Other Special Projects in the U. S. Program in Ionospheric Physics .... Harry W. Wells 49
Background and Technical Objectives in Geomagnetism Elliott B. Roberts and David G. Knapp 55
New Experiments Concerning the Geomagnetic Field Extending into Interplanetary Space .... J. A. Simpson 65
Significance of Cosmic-Ray Monitor Observations .... Robert L. Chasson 71
High Altitude Cosmic-Ray Measurements during the IGY E. P. Ney and J. R. Winckler 81
Visual Observation of the Aurora .... Carl W. Gartlein 92
The Night Airglow .... Franklin E. Roach 97
The Rocket as a Research Vehicle .... P. H. Wyckoff 102
The U. S. Pre-IGY Rocket Program .... Herbert Friedman 108
The Satellite Launching Vehicle—Placing the Satellite in Orbit .... John P. Hagen 119
The United States Satellite Tracking Program .... W. H. Pickering 133
Scientific Instrumentation of the Satellite .... James A. Van Allen 142

THE LOWER ATMOSPHERE AND THE EARTH

Sun, Sea and Air: IGY Studies of the Heat and Water Budget of the Earth .... Roger R. Revelle 147
Synoptic Meteorology and the IGY .... Morton J. Rubin 154
U. S. Special Meteorological Studies for the IGY .... Sigmund Fritz 161
Synoptic Studies in Oceanography .... Columbus O'D. Iselin 169
The Seasonal Budget of Water .... Walter H. Munk 175
U. S. Polar Ice and Snow Studies .... Henri Bader 177
Mountain Glaciology .... George P. Rigsby 182
The Crust and Mantle of the Earth .... Maurice Ewing 186
Seismology and the IGY .... Jack E. Oliver 190
Gravity Observations during the IGY .... George P. Woollard 198

THE POLAR REGIONS

The U. S.-IGY Program in the Antarctic .... Laurence M. Gould 203
The United States IGY Arctic Program .... John C. Reed 207

Preface

The present volume assembles a group of papers covering a wide variety of topics in geophysics. These papers were presented at a special symposium, June 28 and 29, 1957, conducted by the U. S. National Committee for the International Geophysical Year just before the IGY program formally began.

The papers are not only of general and historical interest, but many of them contain reports on early results of the IGY. Although the IGY formally began on July 1, 1957, a number of our own projects had been initiated considerably before that time; moreover, certain geophysical research which formed the basis for the IGY departure is also encompassed in this volume. Finally, the papers provide not only the status of our projects at the beginning of the IGY but often present reviews of the general status of a discipline. For all of these reasons, the Committee believes that the present volume may be of value to geophysicists broadly.

On behalf of the U. S. National Committee I wish to express our deep appreciation to the participants in the symposium and especially to the authors who were able to prepare manuscripts for inclusion in this volume. I also wish to acknowledge the extensive and imaginative efforts of Hugh Odishaw, the Committee's Executive Director, and Stanley Ruttenberg, Head of the USNC-IGY Program Office, in arranging the symposium itself and in preparing the material for publication. The Committee is also appreciative of the interest of the American Geophysical Union in the IGY program and for cooperation in publishing this volume, and our thanks are due Waldo Smith, the Union's Executive Secretary, for his able assistance in seeing Geophysical Monograph No. 2 into press.

JOSEPH KAPLAN
Chairman, USNC

Washington, D. C.
June 6, 1958

Solar-Terrestrial Relationships

Walter Orr Roberts

Introduction—Thirty-two years ago the International Research Council recognized the growing importance of solar-terrestrial relationships by organizing a committee to report regularly on new knowledge of the Sun's influences on the Earth. The resulting reports chronicle a steadily expanding sphere of research into the nature of solar emissions and the physics of their effect on the Earth.

Back in 1925 solar influence on geomagnetism and auroras were considered to be well established though not well explained. Today we are still far from understanding how these auroral and geomagnetic influences operate. We know, however, of a great number of additional, reliably established solar effects on Earth, some of which are more thoroughly understood than auroras or geomagnetic storms. The purpose of this paper is to outline the principal known effects, to list some additional possible solar-terrestrial effects whose relationships are not conclusively established, and to discuss briefly the possible physical mechanisms by which the Sun-Earth effects are transmitted.

Nature of Sun's Emissions

Electromagnetic radiation—The Sun emits electromagnetic radiation over a wide range of wave lengths from x rays of about one Ångstrom wave length to very long radio waves of many meters. The Sun also appears to emit clouds of ions with a wide range of velocities from 'slow' corpuscles of a few hundreds of kilometers per second to cosmic-ray particles possessing a considerable fraction of the velocity of light. The steady, unvarying radiation of the 'normal' Sun contains the overwhelming predominance of the Sun's emitted energy. The emission resembles that from a black body at 6000° K, a figure that closely approximates the surface temperature of the 864,000-mile solar sphere. There is good evidence, nowadays, that short-term fluctuations in this steady heat flow, if there are any, do not exceed 0.3 pct of the energy output. It is this unvarying flux of energy that warms the Earth, drives the winds, provides the vital energy of living things, and generally regulates the course of daily affairs by the geometrical effects of day and night and of the seasons.

There are, nonetheless, important irregular variations in the Sun's electromagnetic and corpuscular output, variations in differing time scales from minutes to centuries. These variations, moreover, are of such character that their consequences are often important to man far out of proportion to their meager energy. They lie at the extremes of the long and short wave length ranges of the electromagnetic spectrum and in the corpuscular emission. Thus they are particularly influential in the Earth's upper atmosphere where radiations like this are absorbed.

Our knowledge of the real nature of the 'anomalous' solar radiation, as the irregularly varying component is sometimes called, derives from scant and indirect evidence, though it is a happy fact that the newer developments of space physics are rapidly bringing us to the time when we shall be able to observe the Sun's anomalous variations directly from rockets and satellites. Solar physics and Earth physics are inextricably entwined in the study of solar variation. More of our information on the character of solar variability has come from study of the terrestrial effects of solar variation than from direct observation of the Sun.

The Sun varies, nonetheless, in many ways that are directly visible, sometimes spectacularly so. Figures 1–4 show some of the more prominent variable solar phenomena. The modern solar physicist recognizes some dozen and more individual and distinguishable features of the Sun that change in characteristic ways and each signals a significant physical process in the solar surface or atmosphere. The difficulty comes, however, when he attempts to put together the different bits of observational information into a self-consistent theoretical picture of the physics of solar fluctuations. Thus far such efforts have led into a morass of inconsistencies and unexplained side-effects.

For example, modern observations of solar flares reveal wide breadths of spectral lines leading to rather firm conclusions that the gases are

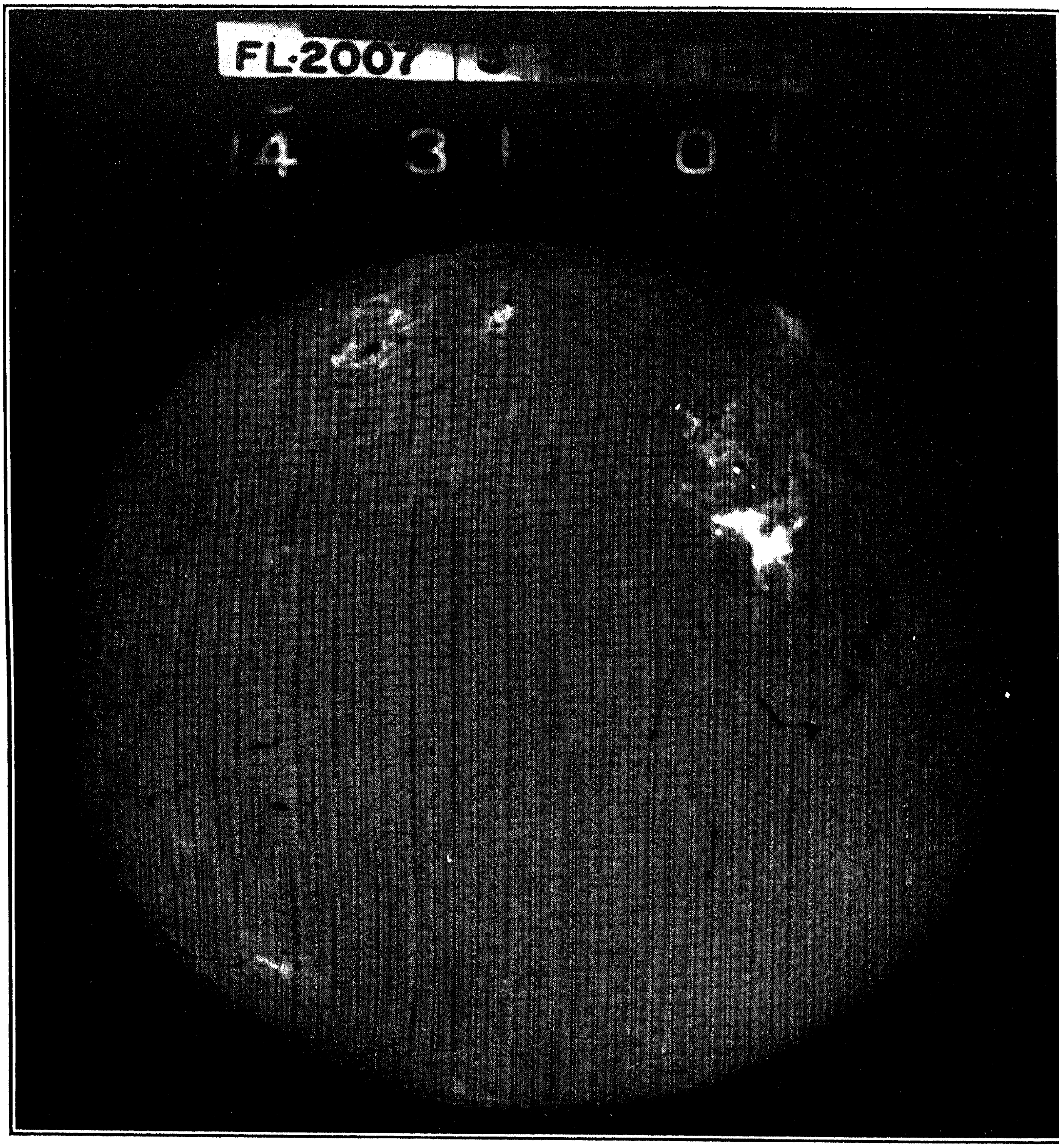

FIG. 1 — A large solar flare photographed at Sacramento Peak Observatory in the light of hydrogen-alpha; such flares frequently rise to maximum brightness in less than five minutes

quite opaque and possess a kinetic temperature of the order of a few tens of thousands of degrees K at the height of the radiating surface. But when the associated coronal spectra are considered, the line widths reveal kinetic temperatures, apparently in the same locations, well above the coronal surroundings and thus well above the normal one to two million degrees K. How are these widely discrepant temperature values to be reconciled? And without a physical theory embracing the two apparently inconsistent facts, how are we to estimate the importance of the radiated x ray emission of the flare? If we believe the coronal temperatures, perhaps, the flare's ionospheric effect is caused predominantly by x rays; if we believe the prominence values, it is more likely to be caused by ultraviolet line-emission.

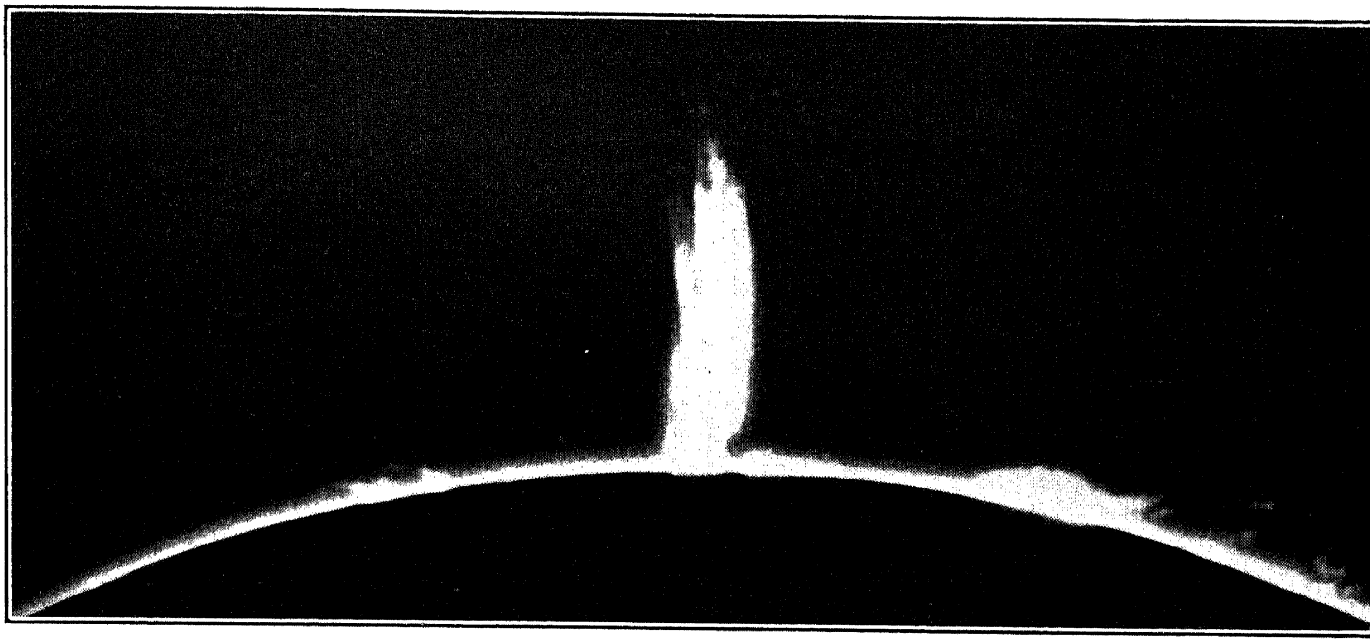

FIG. 2—A giant surge prominence photographed in hydrogen-alpha with the Climax coronagraph of High Altitude Observatory; this prominence was traveling at several hundred kilometers per second away from the solar surface; such ejections undoubtedly represent a part of the solar corpuscular emission

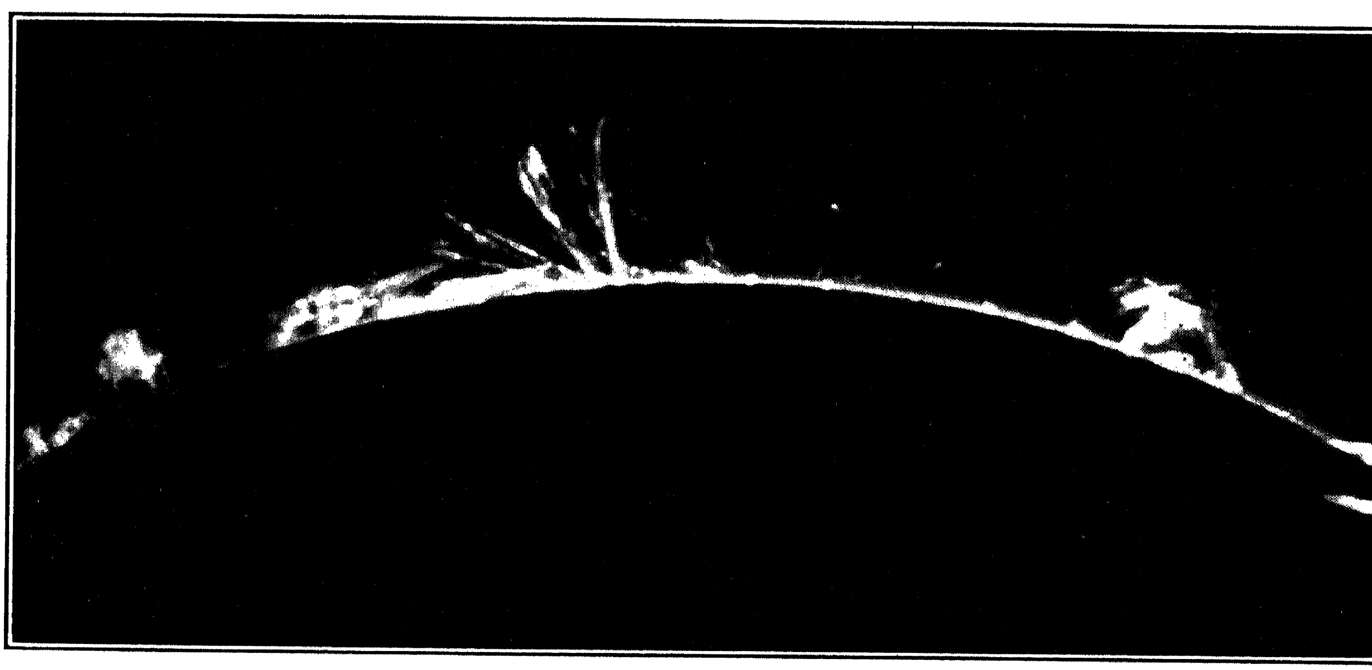

FIG. 3—A solar prominence of the type associated with severe active regions and with strong meter-wave solar radio noise; photographed in hydrogen-alpha at Climax

Corpuscular radiation—Concerning the Sun's high-speed corpuscular emission, recent researches have revealed direct associations between cosmic-ray emission and solar flares. The 'slow' corpuscular emission (velocities from 300 to 3000 km/s) also receives its share of attention nowadays; and, with the greater power lent us by developments in hydromagnetic theory, that is, applied not only to the solar atmosphere but to the near-Earth physics of ion clouds encountering the geomagnetic field, physical theory is gradually pointing the way to understanding larger fragments of observed behavior of magnetic field fluctuation, auroral streamer formation, and induced ionospheric electrical currents. Progress in understanding both the 'slow' emission and cosmic rays depends critically, however, on providing the support and the proper climate for

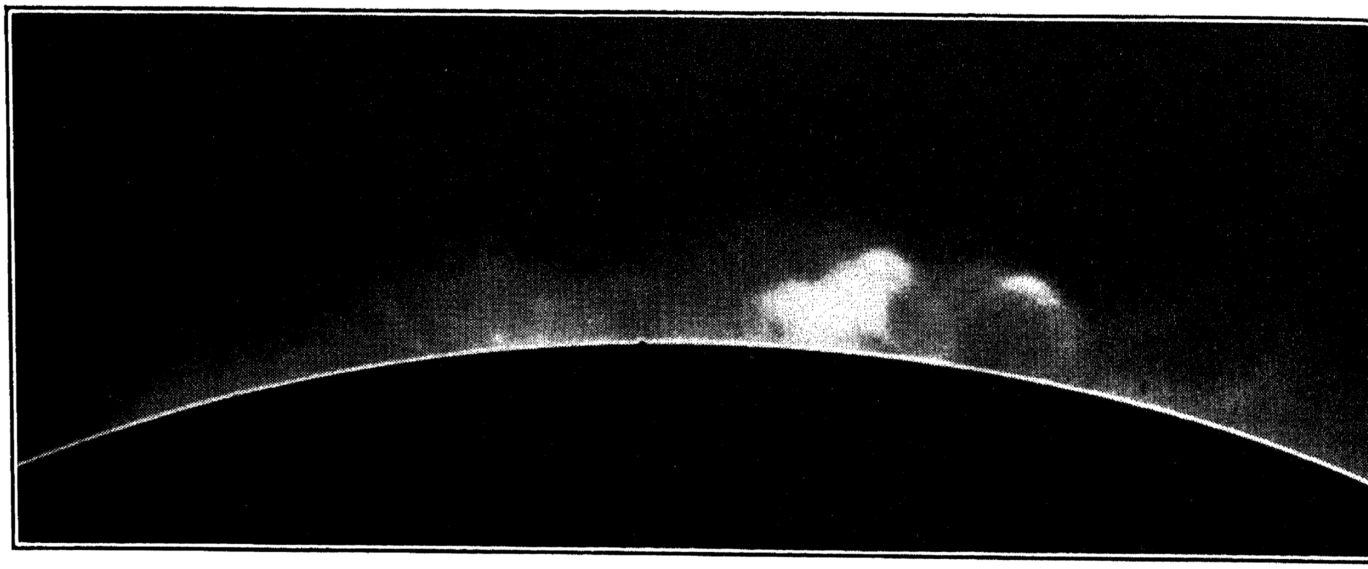

FIG. 4 — A photograph of the great solar active region of the west solar limb of November 22, 1956; photographed in the monochromatic light of the green emission line of the solar corona at Sacramento Peak Observatory

vigorous advances in fundamental theory. Without this, the newly possible solar and geophysical observations are going to be inefficiently exploited.

SOLAR TERRESTRIAL CONNECTIONS

Solar flares—Solar flares (Fig. 1) produce the most direct and clear-cut of all Sun-Earth effects. When a large solar flare occurs there are instantaneous upper atmosphere effects in the D region of the atmosphere of the sunlit hemisphere. The effects include: (1) a rapid augmentation of the ionization, (2) a lowering of the height of reflection of the appropriate wave length of radio signal, and (3) a fadeout of other frequencies due to complete signal absorption. The effect of flares on radio was first discovered about 1927 independently by Dellinger and by Mögel, and was extensively explored in the 1930's. Mögel also noted the connection of these fadeouts to characteristic disturbances of the Earth's magnetic field known as crochets, first detected in 1859 by the British astronomer Carrington.

The British Polar Year Expedition to Tromso, Norway, in 1932–33 expanded our knowledge to embrace the intimate connection between weakening of radio signal reflections and auroral activity, which was in turn strongly suspected to have a solar origin. The first really clear example of these flare-induced phenomena, however, was discovered on April 8, 1936, when the Mount Wilson Observatory noted a very intense solar flare, accompanied by a radio fadeout of widespread character, and a simultaneous crochet. The following years brought successive examples in abundance. Today we recognize the relation of flares and fadeouts as the most nearly invariable of solar-terrestrial relationships.

There is no doubt that the effects are the result of shortwave solar radiation in the ultraviolet or x ray region (or perhaps both) associated with the solar flare. Most probably a substantial part of the flare emission is in the fundamental line of the hydrogen spectrum, Lyman-alpha at 1216 A. The magnetic crochet is now believed to result from the quickly changed conductivity of the D region, whose ionization is enhanced by the flare radiation.

Nonetheless, riddles still abound. When small flares are examined, some exhibit pronounced fadeouts, others none at all. There are no apparent differences between flares with or without fadeouts, except, as *Warwick* [1955] has suggested, in the height of the flare in the semi-opaque solar atmosphere. *Severny* and *Shaposhnikova* [1954] have also stated that for such flares, the abrupt ones tend to have larger intensity. Records of D region ionization made at the High Altitude Observatory with new IGY instruments suggest that the ionospheric effects of abrupt flares appear to be larger than those of more gradual flares of equal area and brightness.

Flares of very large size (July 26, 1946, November 19, 1949, February 23, 1956) have sometimes produced measurable cosmic-ray increases. In one famous instance (February 23, 1956)

cosmic-ray intensities, integrated over the whole atmosphere and estimated at the top of the atmosphere, rose by a large factor. There was evidence that the flare-produced cosmic rays actually stimulated large ionospheric effects some 15 minutes after the radiational effects of the flare reached the Earth. These flare effects extended throughout the night hemisphere of the Earth in high latitudes.

Ionospheric effects—Many ionospheric effects are found to correlate with the average level of sunspot, flare, and other solar activity (Figures 2, 3, and 4). Ionospheric storms are significantly more frequent during solar maximum than during minimum, and critical frequencies of E, F_1, and F_2 region radio-reflections all appear to be influenced. Obviously the Sun's activity alters the electrical state of the upper atmosphere in a profound manner. Today's research indicates that variations of the F_1 and F_2 regions of the ionosphere are under rather direct solar coronal influence, while the E layer is more strongly controlled by chromospheric phenomena, and the D region by chromospheric disturbances and by photospheric (steady) radiation.

'Sunspot cycle' effects—Space will not permit even a brief summary of all of the reasonably well established solar-terrestrial effects. Most of these, however, exhibit the general 11-year 'sunspot cycle' variation. Some are more subtle, however. A few relations are more pronounced in years of declining sunspot activity, such as the long-sustained magnetic storms generally referred to as M-region storms. The M-region storms and their associated auroras are rather unusual in that they have no obvious visible solar source.

Other relations—The Earth is certainly not only bathed in variable short-wave electromagnetic radiation and impulsively changing corpuscular energy but is also subjected to rapidly changing solar radio noise. It seems highly improbable that the radio noise produces any material atmospheric or terrestrial changes, but possible effects cannot yet be entirely ignored.

Chapman [1957] has also recently suggested a further possible solar influence on the upper atmosphere. It arises from variable amounts of energy transmitted to the Earth's upper atmosphere, perhaps at the F_2 ionospheric level, by thermal conduction in the solar corona. As with corpuscular emission, this energy will be channelled towards terrestrial polar regions by the geomagnetic field. No direct experimental confirmation of this effect is known, but IGY researches have good prospects of gathering relevant evidence.

An important possible cosmic-terrestrial effect has also been suggested recently by *Bowen* [1956], who has offered data purporting to show that meteoric dust introduced in the Earth's atmosphere increases world rainfall on certain annually recurrent key days. This interesting new idea opens a wide field of speculation about conceivable astro-geophysical relationships originating far beyond the Sun.

Role of IGY

The role of IGY in advancing the state of knowledge of solar-terrestrial relations can scarcely be exaggerated. We approach a better knowledge of solar phenomena by means of rocket and satellite observation of radiations from the sun accompanying various solar events. The experiments of the Naval Research Laboratory groups directed to x ray and Lyman-alpha observation during solar flares are one example of this. On the other hand, the vastly improved observations of the terrestrial effects of observed solar phenomena will allow many critical tests of the theories of the production of the responsible solar emanations. Simultaneous Arctic and Antarctic observations will be particularly useful for improvement of our theories of the effects of solar corpuscules on aurora, earth magnetism and weather. Thus, we can expect a far better understanding of the sun from our IGY look at Earth.

References

Bowen, E. G., An unorthodox view of the weather, *Nature*, 177, 1121–1123, 1956.

Chapman, S., Notes on the solar corona and the terrestrial ionosphere, *Smithsonian Cont. to Astrophysics*, 2, 1–12, 1957.

Severny, A. B., and E. F. Shaposhnikova, Investigation of the development of chromospheric flares, *Izv. Krim. Ap. Obs.*, 12, 3, 1954.

Warwick, C. S., Flare height and association with SID's, *Astrophys. J.*, 121, 385–390, 1955.

High Altitude Observatory, University of Colorado, Boulder, Colorado

The High Atmosphere

N. C. Gerson

Introduction—Although man is most concerned with its lowest six feet, the Earth's atmosphere stretches away from the planet for some thousands of kilometers. Even with this vast extent, however, half of the mass is concentrated below six kilometers, and only about one-millionth remains above 100 km. At the diffuse boundary with interplanetary space, the temperature is about 1500°K; hot enough to boil off helium and hydrogen but cool enough to retain atomic oxygen. Although tenuous, the atmosphere acts as a protective cushion to life at its bottom. It absorbs harmful radiations, both of corpuscles and photons, meteors, cosmic dust, cosmic rays, x-rays, ultraviolet light, etc., thereby permitting life as we know it to exist on this planet.

The direct effects of the high atmosphere include the occasional meteor or meteor shower, the northern lights, the colorful nacreous and noctilucent clouds, etc., which today are remembered for their esthetic value rather than the supernatural appeal of yesterday. Superficially, there seems little direct contact between the upper atmosphere and man's daily pursuits. Nevertheless, a link of tremendous importance exists between the upper atmosphere and today's technological era. This region allows and controls practically all long distance radio transmissions.

Although in many respects the conventional meteorologist ignores them, the higher atmospheric strata impress themselves more and more upon his and the layman's consciousness. Radio communications, electronic navigational systems, radio guidance, and, to a minor extent, even the familiar compass navigation are affected by events in the high atmosphere.

A study of the upper atmosphere falls rather naturally into the electromagnetic group of geophysical sciences: auroral physics, cosmic rays, geomagnetism, ionospheric physics, and solar-terrestrial relationships. The sections which follow attempt briefly to describe the importance of these fields and some of their characteristics.

Atmospheric Structure

The atmosphere, far from being a simple gaseous envelope surrounding the Earth, is a churning, complex medium. Several terminologies have been proposed to describe its gross structure, as indicated in Figure 1. All classifi-

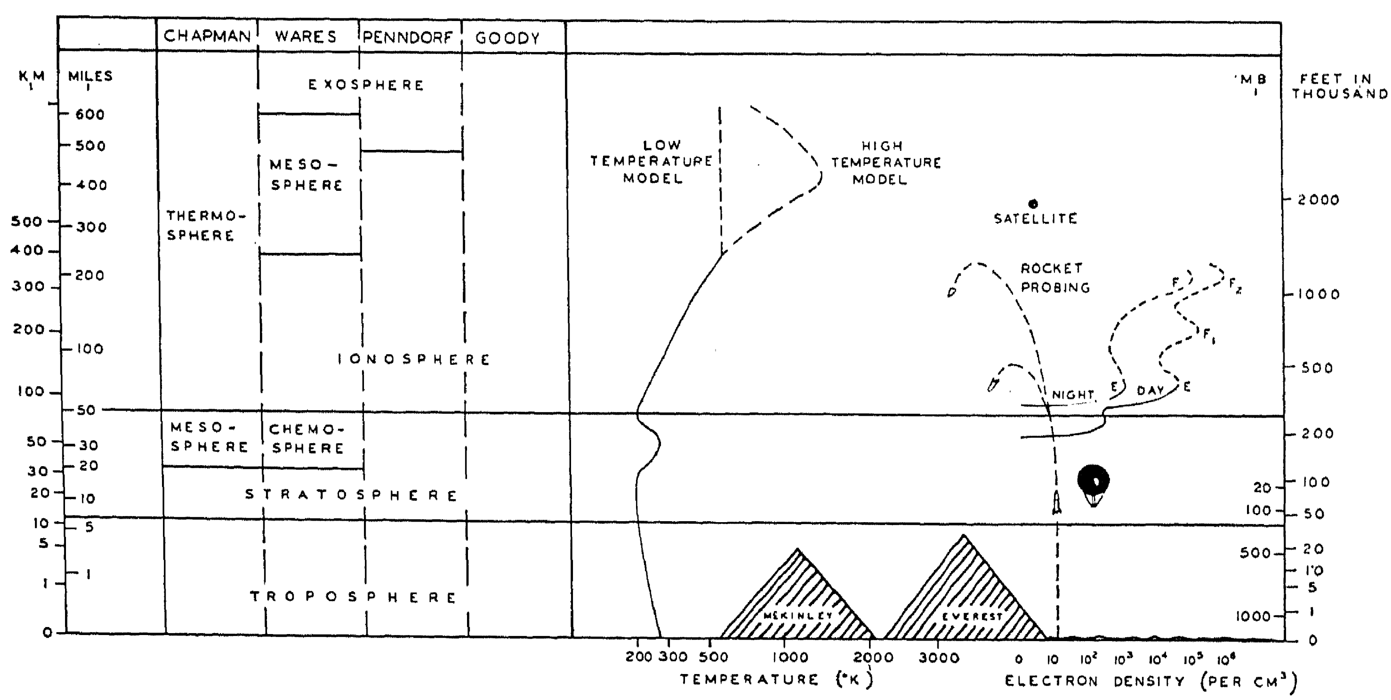

FIG. 1 — Structure of the terrestrial atmosphere from the surface of the Earth to the exosphere

cation systems consider the atmosphere to be composed of a series of non-concentric, superposed shells called '-spheres' separated by transition zones termed '-pauses.'

Everyday weather dominated by water vapor in its three phases is confined to the troposphere. Weather is the result of complex hydrodynamic and thermodynamic processes occurring in the air. Very generally, existing weather patterns over the globe arise from (a) unequal absorption of solar energy from equator to pole, (b) influence of a rotating Earth upon moving air masses, and (c) latitudinal distribution of source and sink regions for minor constituents. For the latter category, for example, more water evaporates from tropical oceanic areas while more condenses and precipitates in middle latitudes.

The Earth's surface is heated daily through the absorption of solar short-wave and atmospheric long-wave radiation. The energy retained by the solid Earth, however, eventually returns to the atmosphere or to space. The solar ultraviolet and terrestrial infrared emissions are selectively absorbed by some of the atmospheric constituents. In most cases, the maximum in absorption is confined to a relatively narrow altitude range because of (a) the exponential increase in atmospheric density with decreasing altitude, and (b) the approximately exponential increase in absorption with increasing penetration of the radiation.

Infrared radiation of the Earth or Sun is absorbed largely by the water vapor, carbon dioxide, and ozone of the troposphere and stratosphere (where these constitutents have their greatest concentration). As both the Earth and the atmosphere reflect or reradiate practically all impinging energy, the net energy budget of the planet is essentially zero.

Although the stratosphere has always been idealized as an isothermal region, innumerable observations have disclosed appreciable departure from the isothermal model. This region is thickest over the poles and thinnest or even absent over the equator. The lower stratosphere contains meandering jet streams, appreciable clear air turbulence and the highest cirrus clouds.

In thermal structure, the troposphere roughly conforms to an adopted temperature decrease of 6.5°K/km, while the stratosphere is deemed roughly constant [*Minzner* and *Ripley*, 1956; *Rocket Panel*, 1952; *Warfield*, 1947]. Considering the ground temperature as the first maximum, a second temperature maximum occurs near 50–60 km (Fig. 1). A second important minimum is found near 80 km. The temperature decreases at a rate of about 3°K/km between about 50 km and 80 km. The distortion of meteor trails, the movement of noctilucent clouds, and drifts of ionospheric irregularities imply the existence of winds and turbulence above 50 km. The D ionic layer is found near 80 km. The emissions of sodium, molecular oxygen, hydroxyl, and atomic oxygen begin below 80 km and extend to higher altitudes [*Chamberlain*, 1956].

The relatively large ionic densities found in the ionosphere seem stratified into layers. These ionic layers allow the reflection of radio waves having a frequency less than about 30 mc/s. Most meteor trails appear in the altitude range 50–150 km, and by far the most common location of the lowest boundary of auroras is found near 100 km.

Important changes in atmospheric composition occur near 100 km. Molecular oxygen dissociates into the atomic form, lowering the average molecular weight of air from 28.90 to 23.95 (for complete dissociation of O_2). A large number of contaminants (proportionately minute in comparison to the principal atmospheric constituents) is introduced by meteors. The contaminants may be of great importance in view of their possible influence on the physics and chemistry of the stratum above 50 km. The electrical current systems that cause geomagnetic variations are generally believed to exist either near 80 km or high in the ionosphere. The absolute number density of electrons above 400 km is less than that found in the ionosphere, but proportionately greater than that occurring below 400 km. Solar radiation, especially in the far ultraviolet, is intense in the upper regions of the ionosphere.

At very high altitudes, a fraction of the neutral atoms and molecules moving upward never experiences a collision within the atmosphere. Particles travel outwards in very long orbits, but eventually return to the atmosphere under the influence of gravity. The center of this collision-free zone is known as the critical level [*Mitra*, 1948]. Above it exists the isothermal exosphere or the outermost fringe of the atmosphere. The mean free path of molecules at an altitude of 1000 km is of the order of tens or

hundreds of kilometers, and increases very rapidly with increasing altitude.

The propagation of very low frequency radio waves channeled along the Earth's magnetic lines of force occurs through the ionosphere, exosphere, and interplanetary space. Radio energy at these long wave lengths may propagate by this means whether it originates by lightning, extraterrestrial effects, or by man-made transmitters. These frequencies may also originate in the Sun or in solar ejecta, and be focussed towards the Earth by the magnetic fields carried along with the ejected material.

Atmospheric Composition

The principal components of the dry atmosphere below about 80 km are, by volume: N_2, 78 pct; O_2, 21 pct; A, 0.94 pct; and CO_2, 0.03 pct. The remaining identified constituents, existing in percentages of 10^{-3} or less, include Ne, He, CH_4, Kr, H_2O, HDO, N_2O, Xe, O_3, I_2, dust, and bacteria. Isotopes of carbon, oxygen, and other elements in detectable amounts are also present. With increasing altitude above the tropopause, some of the polyatomic molecules become dissociated, while new compounds are formed (during daylight) through photosynthesis. It is believed that a veritable host of new compounds are photochemically created at altitudes above 30 km [*Paneth,* 1937, 1954].

In addition, many foreign particles constantly rain upon the atmosphere and remain as contaminants. Some of the elements injected by meteoroids, cosmic dust, cosmic-ray primaries, or auroral primaries include Fe, Si, Mg, N, S, Ca, Al, Co, Na, Cr, Mn, K, P, Ti, Cl, Cu, H, O, and C. Insofar as cosmic-ray primaries are concerned, all elements in the periodic table up to the atomic weight of Fe, and many beyond, have been detected. Of the auroral primaries only H has been observed, but others are anticipated. Obviously the total integrated percentage of the contaminants in the atmosphere

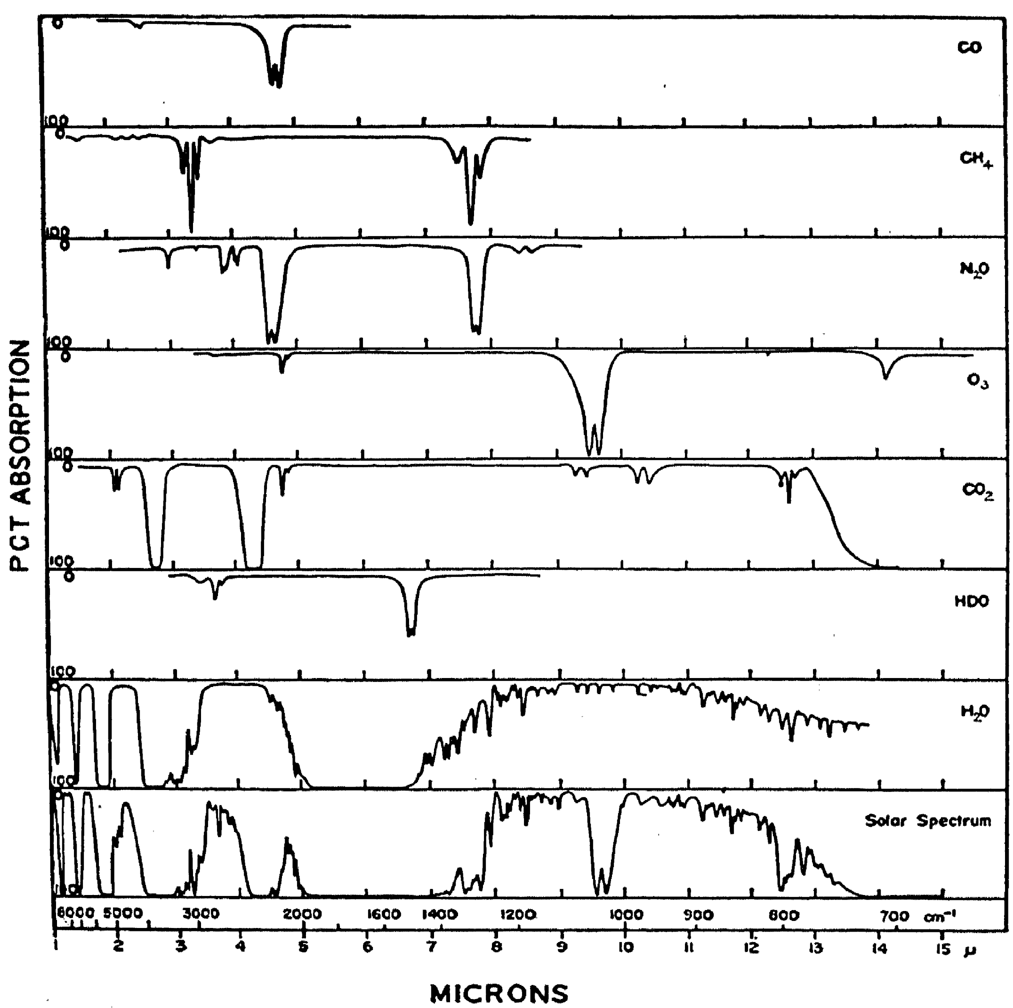

FIG. 2 — Infrared absorption spectra of the atmosphere and some of the atmospheric constituents

is minute. Nevertheless, their importance as possible catalytic or quenching agents for some types of chemical reactions in the atmosphere should not be minimized.

The atmosphere behaves as a gigantic absorption cell placed between the Earth and extraterrestrial radiations. The properties of this telluric absorption cell have never been duplicated fully in the laboratory. Analysis of the solar absorption spectrum in the infrared, particularly with high-dispersion spectrometers, has allowed the identification of several trace atmospheric compounds. (Indeed, infrared spectroscopy of the Sun is an important tool for detecting small concentrations of unsymmetrical molecules in the atmosphere of either the Earth or the Sun.) The infrared atmospheric absorption spectrum is shown in Figure 2 which also contains the spectra of some of the most important absorbers [*Shaw, Oxholm,* and *Claassen,* 1951]. Absorption of infrared is mass dependent, resulting in most of the absorption taking place in the lower atmosphere.

The most important of known photochemical reactions occurring in the atmosphere below about 120 km are: (a) formation of ozone, (b) dissociation of H_2O, (c) dissociation of CO_2, (d) probable formation of NO, and (e) dissociation of molecular oxygen. Undoubtedly the relative concentration of any of these products is a function of altitude, latitude, solar zenith angle, and solar activity. However, only in the case of ozone has the distribution with space or time been investigated, and then but partially.

The distribution of the minor photochemically produced or dissociated compounds, CH_4, CO, NO_2, O_3, and O in the oxygen dissociative region, at any given altitude probably varies over the globe with time of day and time of year. Their concentration is influenced by diffusion and transport within the atmosphere in addition to being controlled by changes in the intensity of solar radiation. An indication of the global distribution of the only minor constituent measured, ozone, is given in Figure 3. Appreciable variations in the ozone concentration occur over the Earth, and similar variations may be expected in the concentration of other minor constituents. The maximum concentration of ozone occurs in the altitude range 20–25 km [*Bates,* 1954; *Regener, Paetzold,* and *Ehmert,* 1954]. Oxygen dissociation takes place in a

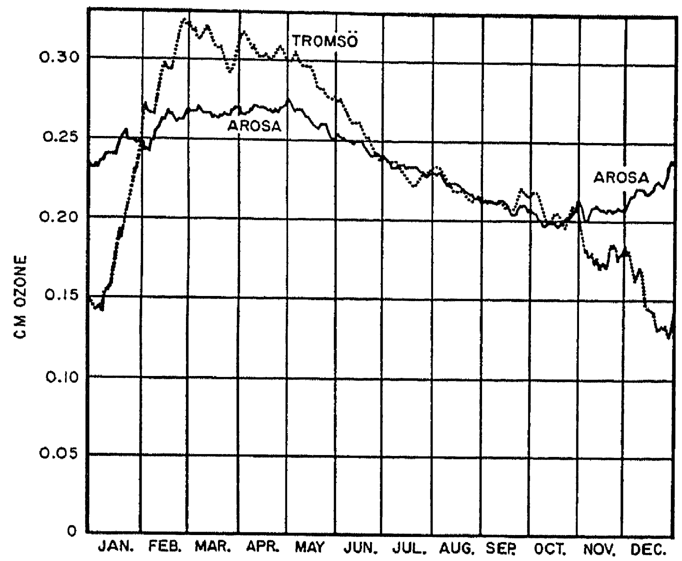

FIG. 3 — Distribution in the concentration of ozone at Tromsö and Arosa during the year; units are in 10^{-3} cm of ozone

rather narrow zone near 100 km. A summary of several determinations of ozone density as a function of altitude is revealed in Figure 4 where both balloon and rocket results are graphed. The difference between the various observations undoubtedly is a true difference existing in the atmosphere at the place and time of observations.

ATMOSPHERIC DYNAMICS

Like the oceans, the fluid atmosphere at all altitudes is subject to forces and stresses that result in rather complicated motions. The presence of small- and large-scale circulation patterns is well known in the troposphere. Similar conditions found at higher altitudes were first suspected from the violent contortions observed in persistent meteor trains [*Whipple,* 1952]. Additional examinations of the high atmosphere have revealed that winds or drifts also occur to at least 400 km, the present maximum altitude that can be studied. The methods utilized to determine drifts above 20 km are summarized in Figure 5. Some indication of the general circulation around the planet may also be obtained by tracking the movement of radioactive debris remaining at definite altitudes.

A summary of the drift components at various altitudes has been made by including the many different techniques utilized in deriving the drift speeds. In general, a monsoonal effect (that is, a change of direction with change of season) is indicated for middle latitudes. At most alti-

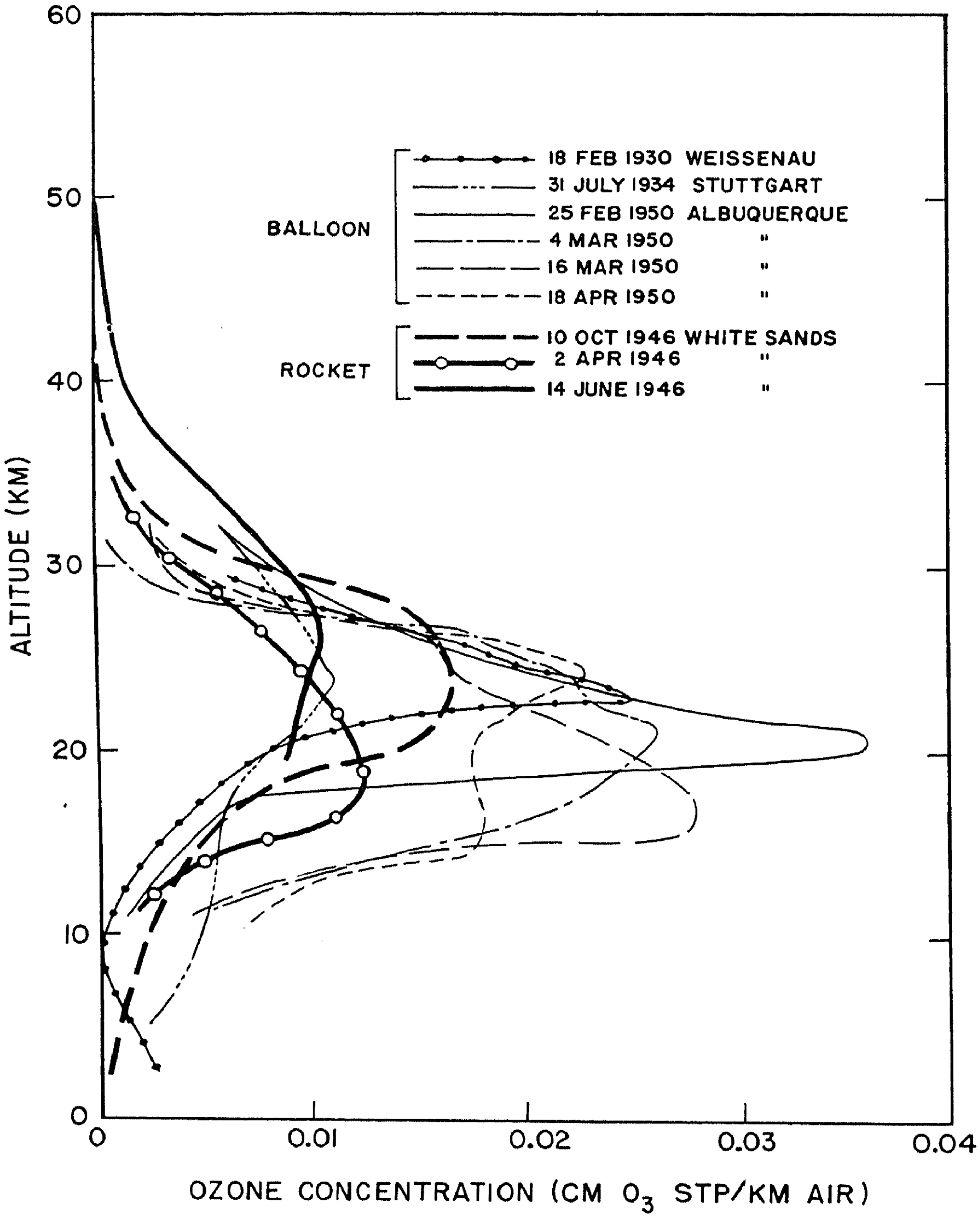

FIG. 4 — The concentration of atmospheric ozone as a function of altitude

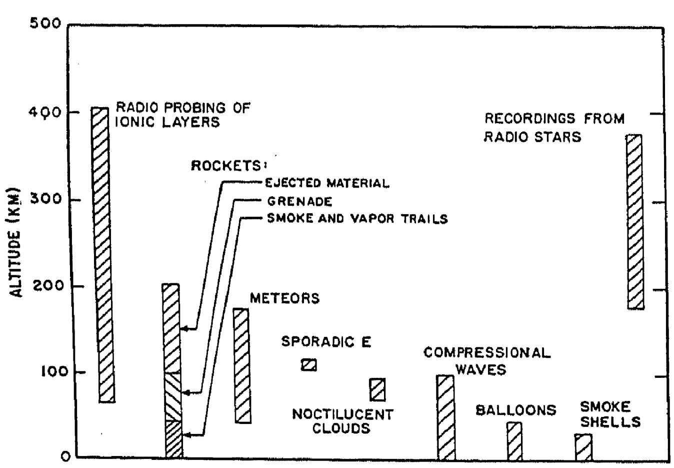

FIG. 5 — Techniques utilized to deduce winds and drifts above 20 km

tudes above 20 km, winds during summer moved from the east and, during winter, from the west.

Some difference in the planetary flow pattern may be anticipated from one solstice to the other because of the marked change in the amount of radiation absorbed by different atmospheric layers. At the winter pole, for example, no direct solar radiation reaches the lower atmosphere for periods of months, and even at 100 km sunlight is absent for about two months. The lack of solar short-wave radiation for such a period of time may allow appreciable changes to occur in the concentration of minor constituents below 100 km. One hypothesis envisions a winter increase in ozone density below 30 km, particu-

larly in polar regions. As ozone is a strong absorber of radiation, the more intense layer presumably is then warmer in winter than in summer.

In general, wind speeds increase with increasing altitude. Also, during winter, greater speeds occur at the higher latitudes, while during summer, greater speeds occur in middle and low latitudes. The prevailing direction of drifts deduced from studies of sporadic E and noctilucent clouds (at about 100 km and 80 km, respectively) is from the east during summer.

A model of the high altitude atmospheric circulation proposed by *Kellogg* and *Schilling* [1951] contemplates a complete reversal in wind direction between summer and winter. Equinoctial months represent a transition period. This monsoonal effect is ascribed to a greater energy absorption during winter by a more concentrated polar ozone layer. The model also considers subsidence (arising from a convergent flow) over the winter pole, and upward movements (arising from a divergent flow) over the summer geographic pole. However, this particular problem is not yet solved.

High-altitude drift speeds have been derived from examinations of the movement of auroral and airglow patterns across the sky. Whether the resulting motions are true winds, the movement of excitation patterns, or other types of non-air mass movement is not settled. Auroral motions may indicate the successive arrival of bursts of auroral primaries into the atmosphere, each burst being slightly displaced in time and space from the previous one.

The determination of movements or drifts in the ionosphere has been attempted by several techniques; namely, observations on sporadic-E trajectories, observations on the motion of ionic irregularities, observations on the drift of ionized meteor trails, etc. As in the troposphere, movements in the ionosphere may be local or large scale. In studying the general planetary circulation pattern at high altitudes, *Gerson* [1956a, b] has indicated that movements up to 200 km may be very similar to those found at lower levels. Thus, cyclonic and anticyclonic systems and jet streams may be present from the troposphere to the ionosphere. Above 400 km motions become predominantly hydromagnetic, with the Earth's magnetic field exercising a strong control over the fluid movements. High-altitude motions contain solar and lunar tidal components. In some instances, consistent diurnal drift variations may be related to these tides. At 100 km the magnitude of the lunar-tidal oscillation may be 100 times greater than that observed at the ground.

Some suggestions have been made that winds at altitudes of 80 km or more can affect the lower atmosphere, perhaps by dragging it through viscous coupling. This suggestion seems difficult to accept. Over 95 pct of the atmospheric mass lies below 20 km, and over 99 pct below 100 km. The prospect of motions in the ionosphere affecting the lower atmosphere seems remote.

Aurora and Airglow

General—One of the foremost objectives of the International Polar Year of 1882–83 was a better understanding of the aurora borealis and its variation with latitude. Observations of the First Polar Year allowed the confirmation of a map showing the isopleths of auroral occurrence over the northern hemisphere; this map has not been appreciably modified since its preparation. Serious study of the aurora was pioneered by the Norwegians in the early period of the twentieth century. Thus, up to about 1940 most auroral research had been undertaken by Norway with noteworthy contributions from France, Germany, and Great Britain. In recent years Canada, the USSR, and the United States have intensified their investigations of this phenomenon.

The initiation and continuance of the aurora is attributed to bombardment of the terrestrial atmosphere by solar particles. After their ejection from the Sun, a stream of corpuscles may engulf the Earth. The Earth's magnetic field is assumed to divert some of the onrushing stream to the polar regions. The particles then rain upon the Earth in the two auroral zones which encircle the north and south geomagnetic poles, respectively. In spectroscopic analyses of the aurora, protons are the only non-atmospheric atoms thus far observed.

In penetrating the atmosphere, auroral primaries encounter atmospheric atoms and molecules. The latter may then be excited (bound electrons being raised to higher energy states) or ionized (an outer electron being lost entirely). Returning to their normal energy states a fraction of a second later, excited atmospheric particles emit their characteristic radiations. The

continuing flux of incoming auroral primaries allows a repetitive excitation-deexcitation process; this mechanism is one means of producing the constantly changing patterns of an auroral display. The principal auroral emanations arise from nitrogen and oxygen.

Most, if not all, visible auroras are accompanied by an invisible ionized aurora. The 'electrified curtain' or ionized aurora on many occasions cuts through the normal ionic layers which usually reflect radio waves. However, the ionized aurora may act to absorb high-frequency (HF) radio waves. The absorption of radio energy during periods of auroral or geomagnetic activity is known as a polar radio blackout. Such blackouts are fairly common in polar regions (particularly during the peak of the sunspot cycle) where they may persist for days, until the spray of solar bombarding particles and their after effects cease.

Considerable effort is still required before a full understanding of all physical processes associated with the aurora is at hand, or before a complete prediction of (a) the occurrence of auroras, and (b) their influence on radio wave propagation is obtainable.

Auroral investigations may be undertaken photographically, spectroscopically, or by means of radio-wave probings. Analyses of these observations provide statistical and descriptive information (height, color, forms, presence by hours of the day and seasons of the year, etc.); spectral studies disclose those atmospheric particles which are excited during an auroral display. These studies also give insight into the excitation conditions and indicate the temperatures of the excited atoms and molecules. Spectroscopic examinations have proven that solar protons invest the Earth and trigger many auroras. In general all studies are complementary, and together increase the fund of knowledge regarding the high atmosphere.

Observations of aurora and airglow are important to many sciences: for example, chemical kinetics, electrodynamics, spectroscopy, and atomic physics. The upper atmosphere provides many unique experimental conditions which have not yet been duplicated in the laboratory. The first discovery of several emission lines was made from analyses of auroral or airglow spectra [*Meinel*, 1951b]. These studies allowed, for example, identification of the Meinel band systems of molecular nitrogen, the atmospheric band systems of molecular oxygen, and some transitions of the hydroxyl molecule (OH). Investigations of the atmospheric absorption spectrum of the Sun similarly yielded data from which the constants of the carbon dioxide molecule and the structure of the ozone molecule were determined.

The faint, non-auroral emissions of the night atmosphere have been termed the night airglow. Its intensity is considerably weaker than that of an aurora. (A bright aurora on some occasions may have an intensity equaling that of the full moon.) Night airglow radiations may arise from the release of solar energy stored by the atmospheric atoms and molecules during sunlight. These emissions may also arise from the constant peppering of the high atmosphere by cosmic dust or interplanetary ions. The intensity of the night airglow is a function of four-space; it varies appreciably with time and location over the globe and at any location the color and brightness of the night airglow change constantly.

Studies of the aurora and airglow also have importance in other fields. The general background light intensity of the atmosphere and sky (the background 'noise level') is collectively known as the sky visibility. Knowledge of the variation in sky visibility throughout the 24-hour period is of great importance to astronomers, for example.

Airglow—On a clear, dark, moonless night, some light falls upon the Earth from the sky. This night skylight is composed of blended radiations from both terrestrial and extraterrestrial sources. The latter include, for example, zodiacal light, galactic light, and starlight (resolved or unresolved). Airglow comprises the non-auroral atmospheric luminosities emitted above about 60 km. As a rough guide, the ratio of intensity of sunlight: moonlight: night skylight is $10^6:1:10^{-6}$.

The airglow is emitted continually during day and night. However, it cannot be seen from the ground in daylight because of the intense scattering of sunlight by the lower atmosphere. Attempts to measure the brightness of the day airglow by rocket borne experiments have not been too conclusive. Theoretical considerations indicate that the airglow should be much more intense by day than by night. The stronger radiations are expected because of the presence

of sunlight: absorption of short-wave solar emissions causes resonant and fluorescent excitation of the atmospheric particles.

During twilight the intensity of some airglow features changes from, for example, the very high daylight values to the low background level found at night. These nocturnal emissions may arise from the release of the potential energy of sunlight (stored by atmospheric particles on being raised to higher energy states). They also may arise from the scattering of ultraviolet light back into the atmosphere by interplanetary atomic particles. Other airglow radiations undoubtedly are produced independent of solar energy; that is, collisional excitation of atmospheric atoms and molecules by cosmic material (dust and ions) penetrating the atmosphere. This mechanism may account for the strong sodium emanations.

The strongest radiations of the night airglow arise from two trace constituents present in the atmosphere in rather minute concentrations: sodium and hydroxyl. In general, contributions to the night airglow include the infrared emissions of OH, the atmospheric and Herzberg bands of molecular oxygen, the green and red lines of atomic oxygen, and the sodium doublet. It has been suggested that the Schumann-Runge bands of molecular oxygen are also present. Hydroxyl bands have been identified well out into the infrared (to two microns) [*Chamberlain* and *Meinel,* 1954]. Although band systems of molecular nitrogen seem to be absent, the first negative band may occur. Stellar absorption lines have been identified in spectra of the night skylight.

Examination of the continuum, that is, the blue and violet regions of the airglow spectrum, has received considerable attention, but only recently has a reasonable explanation been found. A detailed comparison of the night skylight spectrum with other stellar and galactic sources indicates that the continuum probably arises primarily from zodiacal light and starlight. Nevertheless, a very weak continuum radiated from the Earth's atmosphere itself may still be present [*Chamberlain* and *Meinel,* 1954].

The greatest difference between the twilight and night airglow radiations is found in the red lines of atomic oxygen and in the sodium doublet. Both are enhanced during twilight. The first negative bands of N_2^+ also appear strongly in twilight. An enhanced line in the green portion of the spectrum has been attributed to atomic nitrogen.

Airglow emissions are characterized by their spatial lack of homogeneity. On most occasions a patchy appearance is found, with relatively bright and dark areas moving across the sky. The average intensity of the background luminosity over the sky varies from day to day, with latitude, and with season.

Emission altitudes of specific airglow radiations are somewhat controversial. Most techniques utilized in determining the altitude have possessed deficiencies; the assumptions utilized to overcome the deficiencies unfortunately influenced the results [*Chamberlain* and *Meinel,* 1954]. However, recently determined altitudes of the emitting layers are: sodium, 80–310 km; Herzberg bands of O_2, 200–350 km; atmospheric bands of O_2, 70–300 km; hydroxyl bands, 70–300 km; atomic oxygen (red), 65–1000 km; and atomic oxygen (green), 62–1000 km. (These altitude ranges include the extremes of values reported in the literature.)

Auroral statistics—Observations of the polar aurora have shown that it appears most frequently in two primary auroral zones located about 23° from the geomagnetic poles. Although observations have not yet confirmed its existence, a secondary, inner auroral zone has been postulated. The secondary zone is thought to occur at higher latitudes than the primary zone.

Most information regarding the aurora has been obtained from studies of the aurora borealis. Much less is known about the aurora australis although in most, if not all, respects the two should be very similar. With relatively few exceptions, the height of the lower border of an aurora in or near the auroral zone is about 100 km. Low-latitude auroras exist at higher altitudes. The greatest altitude at which auroras have been observed (the top of sunlit auroras) is about 1100 km [*Störmer,* 1955].

Several different auroral forms are known: homogeneous arcs, homogeneous bands, pulsating arcs, diffuse luminous surfaces, pulsating surfaces, glows, arcs with ray structure, bands with ray structure, draperies, rays, coronas, and flaming auroras. Homogeneous arcs and a few other types frequently are oriented along, or at a small angle to, the magnetic latitude. Observations have shown that auroral features drift

across the sky sometimes reversing at local midnight. However, it is not clear whether this drift is a true motion of air.

An ionized aurora, whose presence may be determined by radio-wave probing techniques, usually is associated with the visual aurora. Electron concentrations in the ionized aurora may easily attain 10^8 to $10^9/cm^3$. Thus, radio waves at frequencies up to 100 mc/s could be reflected back to Earth rather than escape into space, as happens when they are incident upon the regular ionosphere. Radio amateurs have reported reflections at frequencies near 220 mc/s but still higher frequencies should be usable. Radar reflections from the aurora at a frequency of over 500 mc/s have also been reported.

The seasonal distribution of the visual and ionized auroras are very similar. The maximum of occurrence is found during the equinoctial months and the minimum during the solstices (Fig. 6) [*Gerson,* 1953]. Although radio-wave probings allow the ionized aurora to be kept under surveillance throughout the 24-hour period, the results, surprisingly enough, confirm those obtained from studies of the visual aurora. Auroras occur mainly during darkness with a maximum between about 22h 00m to 01h 00m local time, as shown in Figure 7. The ionized aurora seems to be least evident from about 06h 00m to 12h 00m local time. On many occasions, auroral activity is accompanied by geographically localized magnetic activity. There are also numerous instances where magnetic activity is unaccompanied by auroras, and others when strong magnetic storms are accompanied by vigorous auroras.

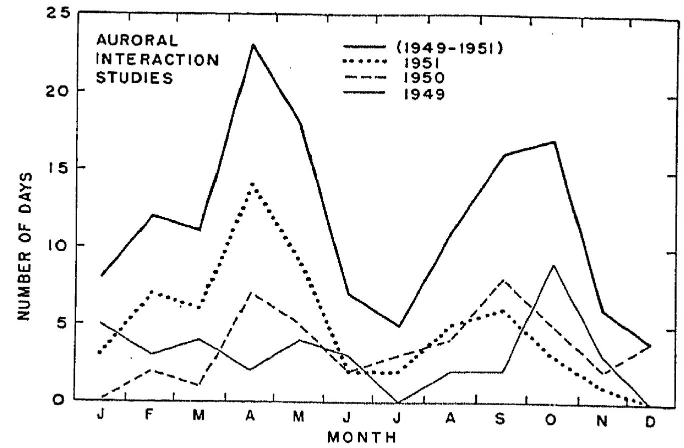

FIG. 6 — Frequency of occurrence of the ionized aurora; the seasonal occurrence of the luminous aurora is practically identical with that of the ionized aurora

Radio noise at a frequency of about 3000 mc/s has been radiated by some auroras. In general, however, the entire frequency range (a) at which noise radiation takes place, and (b) at which radio reflections are possible is not known for the ionized aurora.

Auroral activity is closely linked to the state of the Sun. Auroras are most numerous, most intense, and extend to lowest latitudes at or

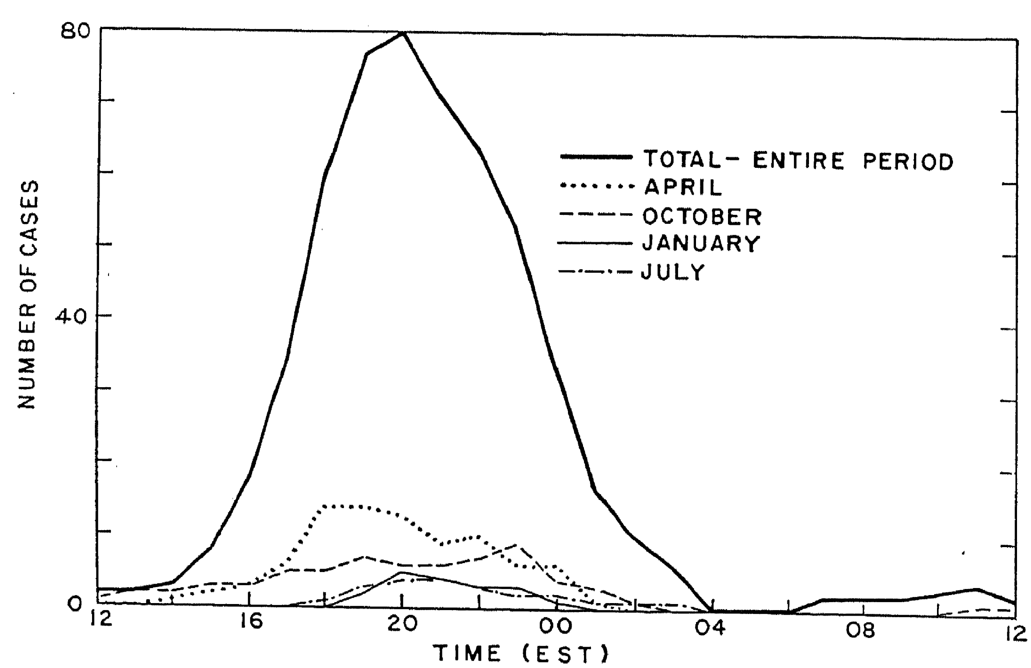

FIG. 7 — Auroral interaction studies, 1949–1951, inclusive; diurnal distribution of the ionized aurora

somewhat after the maximum in solar activity. The aurora is considered to be initiated or produced by a neutral stream of charged particles ejected from the Sun. In the vicinity of the Earth the stream interacts with the Earth's magnetic field. In the interactions, some of the particles are deflected towards the polar regions where they penetrate the atmosphere to form the luminous aurora.

The general problem of the aurora may be subdivided into four portions. The first portion is astrophysical in nature and concerns the mechanics of ejecting material from the Sun. The second portion is in magnetohydrodynamics and includes a study of the movement of the neutral solar stream (of charged particles) from the Sun to the outer limits of the Earth's atmosphere and its interaction with the solar, galactic, and terrestrial magnetic fields. The third is spectroscopic, and comprises the collisional excitation of the terrestrial particles by the bombarding solar particles, and the resulting deexcitation processes. The final portion is electromagnetic and embraces the collisional ionization of the atmospheric atoms and molecules, the diffusion and dissipation of the resulting ionized aurora and the influence of the ionized sheets on incident radio waves.

Because of the basic differences in their excitation, spectra of the aurora and airglow differ in many respects. However, because of the complexity of the auroral spectrum, a correct identification of all auroral radiations has been difficult. In many portions of the spectrum atomic and molecular emissions overlap. Still further confusion may arise when important atomic lines are obscured by strong molecular bands.

Among the strongest radiations of the aurora are the green and red lines of atomic oxygen at 5577A, 6300A and 6364A. Several other atomic oxygen lines may be present but ground based observations do not allow a positive determination. Many lines of atomic nitrogen, and the sodium doublet have been identified [*Chamberlain,* 1956]. The Balmer lines of hydrogen seem irrefutable; from the doppler broadening of the hydrogen lines, the speed of the incoming solar protons near the end of their trajectory was determined as 3×10^8 cm/sec.

The most prominent molecular features of the aurora are emitted by neutral and ionized nitrogen. Radiations of molecular oxygen appear somewhat weak except in the case of auroras penetrating well below 100 km. Emissions of molecular nitrogen are plentiful. The strongest are the first positive bands. The second positive and Vegard-Kaplan bands are present. The first negative and Meinel bands of N_2^+ have been identified. The atmospheric bands of O_2 and the first negative bands of O_2^+ have been confirmed. The spectrum of any two auroras may differ [*Meinel,* 1951a]. The differences arise because auroras may appear at different altitudes (where the atmospheric temperature, density, and composition, for example, are dissimilar), and also because the energy of the bombarding particles may vary.

The Ionosphere

The ionic layers—There are several ionic layers or regions, the D, E, F1, and F2 layers, as shown in Figure 8. A G layer has been reported occasionally as existing in the tropics (at an altitude of about 400 km) but its presence is doubted. The average altitudes of the E, F1, and F2 layers are about 100 km, 200 km, and 300 km, respectively. In addition to these regular layers, cloud-like and abnormal areas of high electron density also exist. The best known is sporadic E ionization (E_s) but auroral E and meteor produced ionization is also found. Diurnal and seasonal statistics on the heights and

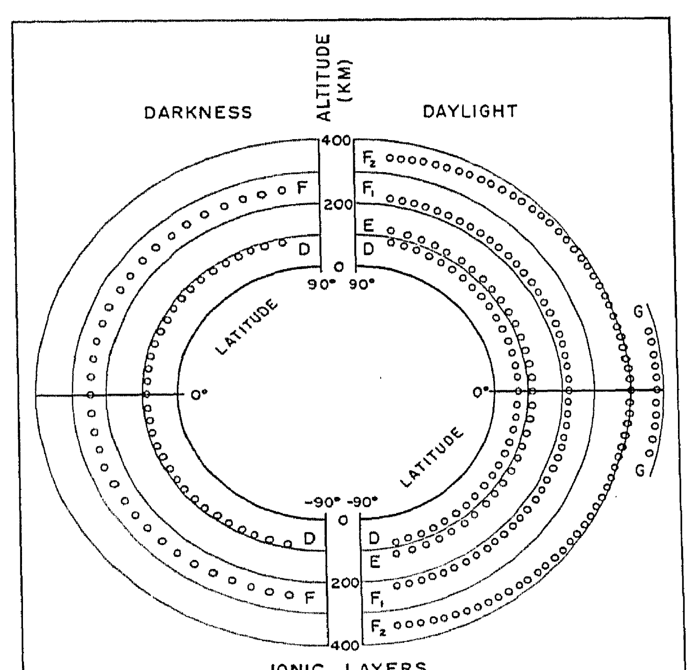

Fig. 8 — Pole to pole cross section through the ionosphere during equinoctial noon

average electron densities are best known for the E and F layers.

The regular layers are formed by solar ultraviolet or x-ray radiations. Generally, the normal layers may be considered to be formed by the normal Sun, and the disturbed ionosphere by a disturbed Sun. Just as any given weather pattern is never identically repeated, so the condition of the Sun (and the state of the ionosphere) never is the same as it was on some previous occasion. Similarities, however, do exist. The concept of daily variation in weather holds for the ionosphere and higher atmospheric shells exactly as it does for the troposphere.

The identity of the particular atom or molecule ionized to form any given ionic layer is uncertain. It is generally believed that molecular oxygen may be ionized to produce the E layer, but the particles involved for the higher layers are unclear. The original theory of ionic layer creation was proposed over two decades ago by *Chapman* [1931]. The effect of solar zenith angle (including both time of day and time of year), and absorption of radiation, were considered. It was then found that the electron density in a layer should be symmetrical about noon, essentially becoming zero at sunrise and sunset. Further, the altitude of maximum electron density should change slowly with time, becoming a minimum at noon (and a maximum at sunrise and sunset).

On comparing the behavior of the actual ionic layers with the theory, it was found that the E layer conforms remarkably well, and the F1 layer shows some deviations. However, the F2 region is highly irregular if not erratic. Only rarely does it follow the simple theory. Prediction of its future state is extremely difficult on many occasions. The electron density of the E and F1 layers is fairly symmetrical about the subpolar point. However, the F2 region is markedly asymmetric. In general, the F2 layer appears to be under much stronger geomagnetic control than the other regions. Typical electron concentrations found in the ionic layers are shown in Fig. 1. However, it should be remembered that with abnormal solar conditions, or in different seasons, the ion densities may vary appreciably from those shown.

Observation has shown in accord with the theory that the greater the solar zenith angle (that is, the closer the Sun to the zenith), the greater the electron density. Thus along the noon meridian the electron density in any layer decreases with increasing latitude (measured from the sub-polar point). During winter in either hemisphere the duration of daylight decreases with increasing latitude; this effect directly influences the daily 'lifetime' and electrification of the ionic layers.

The lowest layer detectable with modern probing techniques is the D region. Its electron density is of the order of $10{,}000/cm^3$ or less. During some flares the increased solar short-wave emissions penetrate to 80 km and produce a greater ionization in the D region. Since the collisional frequency of electron and neutral particles is rather high at this level, the D layer then absorbs most impinging radio wave energy. This mechanism is believed to be responsible for producing sudden ionospheric disturbances (SID) and radio fadeouts.

Several types of ionization found in the ionosphere are not produced directly by solar action. Meteoric ionization, which can be employed for communication purposes, is caused by meteors in passing through the stratum between 50–150 km. Auroral ionization may be considered as the remnants of ionized auroras which dissipate with time. The diurnal and annual variation in meteoric ionization closely follows the diurnal incidence of meteors upon the Earth and the occurrence of meteor showers.

Sporadic E ionization also does not seem to be under immediate solar control. In middle latitudes, it exists in large cloud-like masses which on some occasions may cover appreciable portions of a continent. Studies have been made of its genesis, growth, and dissipation. However, its origin is still unknown. Studies have shown that it may suddenly appear, grow rapidly at the rate of thousands of square kilometers per hour, and finally begin its dissipation. During the growth period it may move rapidly. Individual clouds have been observed for periods of from a few minutes to about a day. Sporadic E displays a strong seasonal dependence with a marked maximum in summer and a weak secondary maximum in December (northern hemisphere). The intense form makes its appearance generally during the evening. Radio-wave probings from many stations allow the size of a sporadic E cloud and its trajectory to be determined. Average speeds of about 250 km/hr ±

50 km/hr seem to be common although much higher speeds have also been found [*Gerson*, 1951, 1953].

The intense form of sporadic E will allow radio-wave reflection at frequencies of 50–150 mc/s at low power. When very large clouds or several small clouds appropriately spaced exist, multihop communication to distances of 4000–6000 km is possible.

The Magnetic Field

Background—Knowledge of the Earth's magnetic field is of practical interest in surveying, navigation, mineral exploration, radio-wave propagation and land-line or radio-telephone communication. Its study is indispensable to the interrelated sciences of ionospheric physics, cosmic rays, auroral physics, and solar-terrestrial associations. Although important to so many sciences, the magnetic field is known chiefly through its intimate connection with the compass.

The directional indication of the compass needle is the simple manifestation of geomagnetism. An undistorted magnetized needle suspended by a thread will take a final position in line with the magnetic lines of force. Use of the compass on this planet is possible because of the existence of the geomagnetic field, the main portion of which resides within the solid earth. Superimposed upon the main field are fluctuations and variations which are believed to originate in electric current systems flowing in and beyond the atmosphere. The atmospheric currents are probably located in the ionic layers between 70–400 km, and are most intense over the polar caps. The interaction of (a) the magnetic fields of the atmospheric and extra-terrestrial current systems, and (b) the main field produces the continuous, innumerable magnetic fluctuations which are so pronounced in high latitudes. At most, the fluctuating components of the magnetic field comprise but several per cent of the total; the main field contribution exceeds 95 pct.

The extraterrestrial or ring current has been proposed to clarify certain features of a magnetic storm and the origination of auroras. The ring current is visualized as flowing around the Earth at a distance of about 30,000 km and as becoming enhanced during auroral displays. The ionospheric and ring currents are considered to produce the general geomagnetic fluctuations. However, the rate, character and implications of most fluctuations are incompletely understood. It also has been proposed that the drift of ionized trails caused by meteors may induce measurable magnetic changes at the Earth's surface; however this hypothesis seems doubtful.

The magnetic field is not only subject to the irregularities and fluctuations mentioned above, but also to certain regular changes that arise from solar and lunar tidal effects. Although they are small, the atmospheric tidal motions move the charged particles of the ionosphere in a predetermined fashion. Statistical analyses of geomagnetic or ionospheric data gathered at a given station over a long period of years allows the tidal movements to be isolated. Slow, predictable daily changes in the direction of the compass needle, as regular as the usual heating and cooling of the lower troposphere during sunlight and darkness, are caused by action of the tidal systems.

Some magnetic disturbances seem to travel over the globe after their origination in the polar regions. The propagation of these phenomena around the Earth may be linked to ionospheric changes and ionospheric current systems. With respect to ionospheric-geomagnetic interrelationships, one of the most reliable precursors of short-term ionospheric modifications is a change in magnetic activity. It might be mentioned that magnetograms from stations near the auroral zone are typified by the continuous superposition of irregular and erratic variations. The cause of these fluctuations is attributed to many local current systems occurring in the auroral zone.

The magnetic field—The source of the Earth's main field is unknown, and its origin constitutes one of the major unsolved problems in geophysics. It undergoes long term, secular variations which may be caused by (a) hydromagnetic effects associated with slow convective movements in a possible conducting fluid core of the Earth; or possibly (b) slow, directed movements of holes in a semi-conductor planetary core. Although recent work favors the former concept, the problem is by no means resolved.

Examinations of rock magnetism indicate that the principal northern dip pole has shifted its position with time. According to some studies, this pole migrated during geologic time from the western Pacific Ocean to its present location

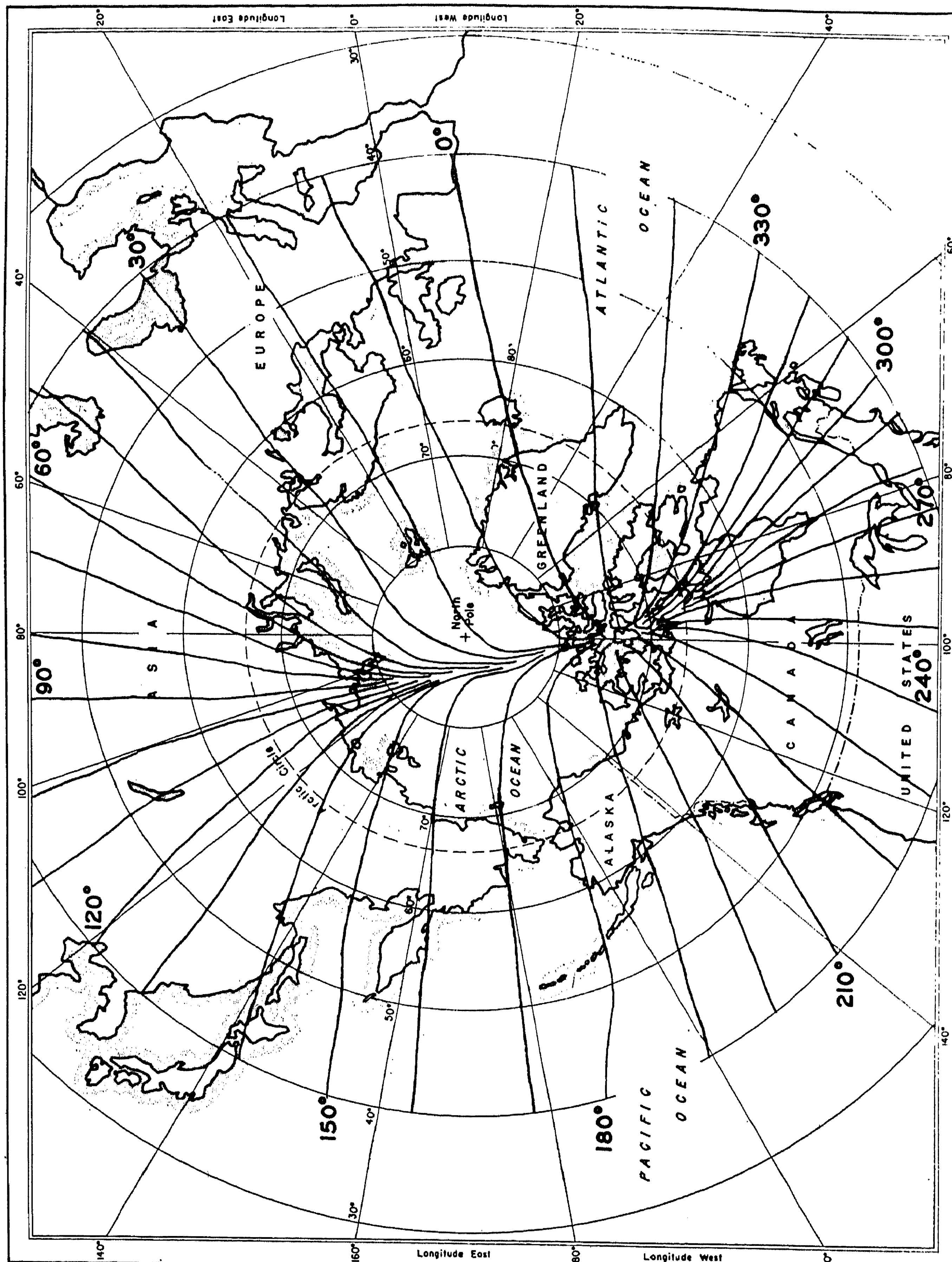

FIG. 9 — Static anomaly in the Earth's magnetic field near the principal northern dip pole

near the central Canadian Arctic Coast. Today, its position is considered as an average position; it seems to wander diurnally and seasonally. In general, the magnitude of the wandering is small, but on some occasions (near the dip pole) the declination can go through 360°. These relatively short-time changes probably arise from the atmospheric current systems.

Although the exact height of the currents causing the fluctuating components is uncertain, certain studies indicate that they may be concentrated near the E ionic layer. The currents giving rise to the disturbance daily variations have been idealized as flowing east and west along the equator, and north and south along the noon meridian. They are of the order of 100,000 amperes in middle and low latitudes, attaining values of about 475,000 amperes over the polar caps. The current systems responsible for the storm time variations have been depicted as increasing with latitude, from very small values at the equator to about 150,000 amperes at the poles. As would be expected, these theoretically deduced currents become seriously modified during the periods of geomagnetic storminess. As would be expected, the tidal changes are superimposed upon the disturbance variations and storm time fluctuations.

The location of the two principal magnetic dip poles, which are not diametrically opposite, is at 76°N, 102°W, and 68°S, 148°E, respectively. A remarkable feature of the magnetic field is the marked static anomaly which exists in the northern hemisphere as a ridge of high horizontal magnetic intensity extending from the northern principal dip pole across the Arctic Ocean into Siberia (Fig. 9). The absolute value of the magnetic field near the dip poles is close to 0.6 gauss, and near the equator, about 0.3 gauss.

Analysis of the magnetic field recordings measured during a given year (or epoch) at many points on the Earth allows the strength of the equivalent magnetic dipole to be derived. Assuming that the equivalent dipole is located at the center of the Earth, the intersection of the dipole axis with the Earth's surface defines the geomagnetic poles. On the basis of the last determination, the geomagnetic poles were located at 78.6°N, 70.1°W, and 78.6°S, 109.9°E, respectively. In considering the Earth as a magnetic dipole in space, and the magnetic interaction with charged particles, the geomagnetic dipole is invariably utilized. Needless to say, the geomagnetic poles are extremely useful in interpreting auroral, ionospheric, and cosmic-ray observations.

Because of the presence of the terrestrial magnetic field, certain investigations of space in the vicinity of the Earth are possible. One type of study utilizes the interactions between the magnetic field and charged particles traveling towards or in the vicinity of the Earth. In general, the greater the speed and mass the less the interaction. Cosmic-ray primaries generally being of high energy 'see' the Earth's field at considerable distances from the planet. Thus, the existence of average, large-scale temporal or spatial inhomogeneities that are not clearly evident at the Earth's surface may be detected from selected observations on cosmic-ray primaries. One such study recently completed involves a determination of the cosmic-ray equator; that is, the magnetic equator as seen by cosmic rays. If the Earth's field were uniform and could be reduced to a true magnetic dipole whose center was at the center of the Earth, the cosmic-ray equator and the geomagnetic equator would be identical. However, preliminary results reveal that the two are different. Investigation of this difference will reveal additional information on the character of the magnetic field at great distances from the Earth.

Another type of study is an examination of whistlers, clicks, dawn chorus, etc. Each is an onomatopoeia for a particular radio noise clearly audible when using special receivers. Whistlers have their origin in lightning discharges. The radiated low-frequency radio wave energy (1–30 kc/s) may be channeled along the magnetic line of force from its point of radiation to the conjugate point in the opposite hemisphere. Many successive reflections may occur (over fifteen have already been reported) as the energy travels from one hemisphere to the other. As some magnetic lines of force extend outwards from the Earth for tens of thousands of kilometers, analysis of the whistler train and its dispersion furnish more information on the characteristics of interplanetary space. Further study of these phenomena at very high magnetic latitudes may indicate emissions which originate in the Sun or in interplanetary space itself.

REFERENCES

BATES, D. R., The physics of the upper atmosphere, *The Earth as a planet,* Univ. Chicago Press, 1954.

CHAMBERLAIN, J. W., Theories of the aurora, *Advances in Geophysics,* 4, Academic Press, New York, 1956.

CHAMBERLAIN, J. W., AND A. B. MEINEL, Emission spectra of the twilight night sky and aurora, *The Earth as a planet,* Univ. Chicago Press, pp. 514–568, 1954.

CHAPMAN, SYDNEY, The absorption and dissociative or ionizing effect of monochromatic radiation in an atmosphere on a rotating Earth, *Proc. Phys. Soc.,* 43, 26–45, 1931.

GERSON, N. C., Abnormal E region ionization, *Can. J. Phys.,* 29, 251–262, 1951.

GERSON, N. C., A note on auroral interaction, *J. Atm. Terr. Phys.,* 4, 81–88, 1953.

GERSON, N. C., General circulation of the high atmosphere, *J. Geophys. Res.,* 61, 351–353, 1956a.

GERSON, N. C., The atmosphere, *USAF Surveys in Geophys.,* no. 75, 1956b.

KELLOGG, W. W., AND G. F. SCHILLING, A proposed model of the circulation in the upper atmosphere, *J. Met.,* 8, 222-230, 1951.

MEINEL, A. B., The spectrum of the airglow and aurora, *Rep. Prog. Phys.,* 14, 124, 1951a.

MEINEL, A. B., The analysis of auroral emission bands, *Astrophys. J.,* 114, 431–437, 1951b.

MINZNER, R. A., AND W. S. RIPLEY, The ARDC model atmosphere, *USAF Surveys in Geophys.,* no. 86, 1956.

MITRA, S. K., *The upper atmosphere,* 2nd ed., R. Asiatic Soc. of Bengal, Calcutta, 1948.

PANETH, F. A., The chemical composition of the atmosphere, *Q. J. R. Met. Soc.,* 63, 433, 1937.

PANETH, F. A., The chemical analysis of atmospheric air, *Rocket exploration of the upper atmosphere,* Pergamon Press, London, 157–158, 1954.

REGENER, E., H. K. PAETZOLD, AND A. EHMERT, Further investigations on the ozone layer, *Rocket exploration of the upper atmosphere,* Pergamon Press, London, 202–207, 1954.

ROCKET PANEL, Pressures, densities, and temperatures in the upper atmosphere, *Phys. Rev.,* 88, 1027–1033, 1952.

SHAW, J. H., M. L. OXHOLM, AND H. H. CLAASSEN, *The solar spectrum from 7–13 microns,* Ohio State Univ. Res. Found., Rept. IA-4, 103, 1951.

STÖRMER, C., *The polar aurora,* Clarendon Press, Oxford, 1955.

WARFIELD, C. N., Tentative tables for the properties of the upper atmosphere, *Nat. Adv. Comm. Aer.,* TN 1200, Washington, 1947.

WHIPPLE, F. L., Exploration of the upper atmosphere by meteoritic techniques, *Adv. in Geophys.,* 1, 119–154, 1952.

U. S. National Committee for IGY, National Academy of Sciences, Washington, D. C., now Trapelo Road, South Lincoln, Massachusetts

Instrumentation for Global Observation of the Sun during the IGY

John W. Evans

Introduction—In the IGY, solar observatories throughout the world are using an extraordinary array of instruments exemplifying the greatest refinement and ingenuity in the exploitation of the technical advances of the past decade. Many of these were constructed specifically for programmed IGY projects. Others are for less formal but equally important non-routine projects, stimulated in large measure by the prospect of world-wide observations of geophysical responses to solar activity.

Solar flare patrol—Perhaps the most promising of the IGY projects in solar observations is the 24-hour-a-day flare patrol. About 30 observing stations, well distributed in longitude, keep the Sun under continuous photographic observation for the purpose of detecting all flares that appear on the visible disk of the Sun. Each station is equipped with a heliograph of standard optical characteristics similar to those of the original flare-patrol telescope which began operation as an experimental instrument at the High Altitude Observatory in 1950. A number of ingenious variations, usually designed for adaptation to an existing mounting or building or some other matter peculiar to the station, have been made at different observatories. Although they are very diverse in physical setup, they are all optically equivalent, and fit into the network plan for homogeneous observations. Probably the most elegant of these is the Lyot Heliograph of the Meudon Observatory (Fig. 1), which has been adopted as a prototype. Several of the stations have exact reproductions of this instrument.

Basically the flare patrol heliograph consists of a 3- to 6-inch equatorial telescope, usually guided on the Sun by a photoelectric servo system, equipped with a birefringent filter and 35-mm cine camera. The filter transmits a band 0.5 to 0.75 A wide, centered on the H-α line of hydrogen. The standard solar-image diameter of 16 mm is sufficient for the easy detection and classification of all flares of importance 1 or more. Photometric standards are impressed on all films for subsequent analysis of particularly interesting flares and plages, but the daily reports will simply give eye estimates of importance according to the criteria established by the International Astronomical Union, along with times and positions. Each station is assigned specific hours of observation during which photographs are taken at intervals of three minutes or less. The assignments are, of course, arranged to insure a full 24-hour coverage, with a generous overlap provided in the hope that at least one station will be observing with clear weather at all times.

The flare patrol represents a fairly modest investment in equipment and the full time of at least one observer for each participating station. The enormous potential value of the results when combined with extensive geophysical observations has fired the enthusiasm of solar astronomers everywhere, and the IGY flare patrol probably represents the most extensive and best coordinated international cooperative effort in astronomy that has ever been attempted. A list of the cooperating stations will be found in the *CSAGI Manual for Solar Activity* published in 1957.

In addition to the flare heliographs, I could present a most impressive list of new instruments for solar observation. Since they are very well covered in a report by *Roberts* [1957] I shall avoid repetition and concentrate on the developments which have made the new instruments possible. Most of this equipment is built around one or more of five basic devices. They are the solar tower, the Lyot coronagraph, the birefringent filter, large and greatly improved diffraction gratings, and solar radio-noise receivers of three types.

Solar tower—The solar tower cannot be classed as a new type of instrument since there are a few which have been in operation for several decades. One of the most modern is described by *McMath* [1953]. The solar tower consists of a vertical telescope, which may be either a reflector or a refractor, into which sunlight is reflected by a pair of flat mirrors. The optical parts are supported by a tower 50 to 150 ft high, and the light passes down a vertical tube to form a stationary non-rotating image

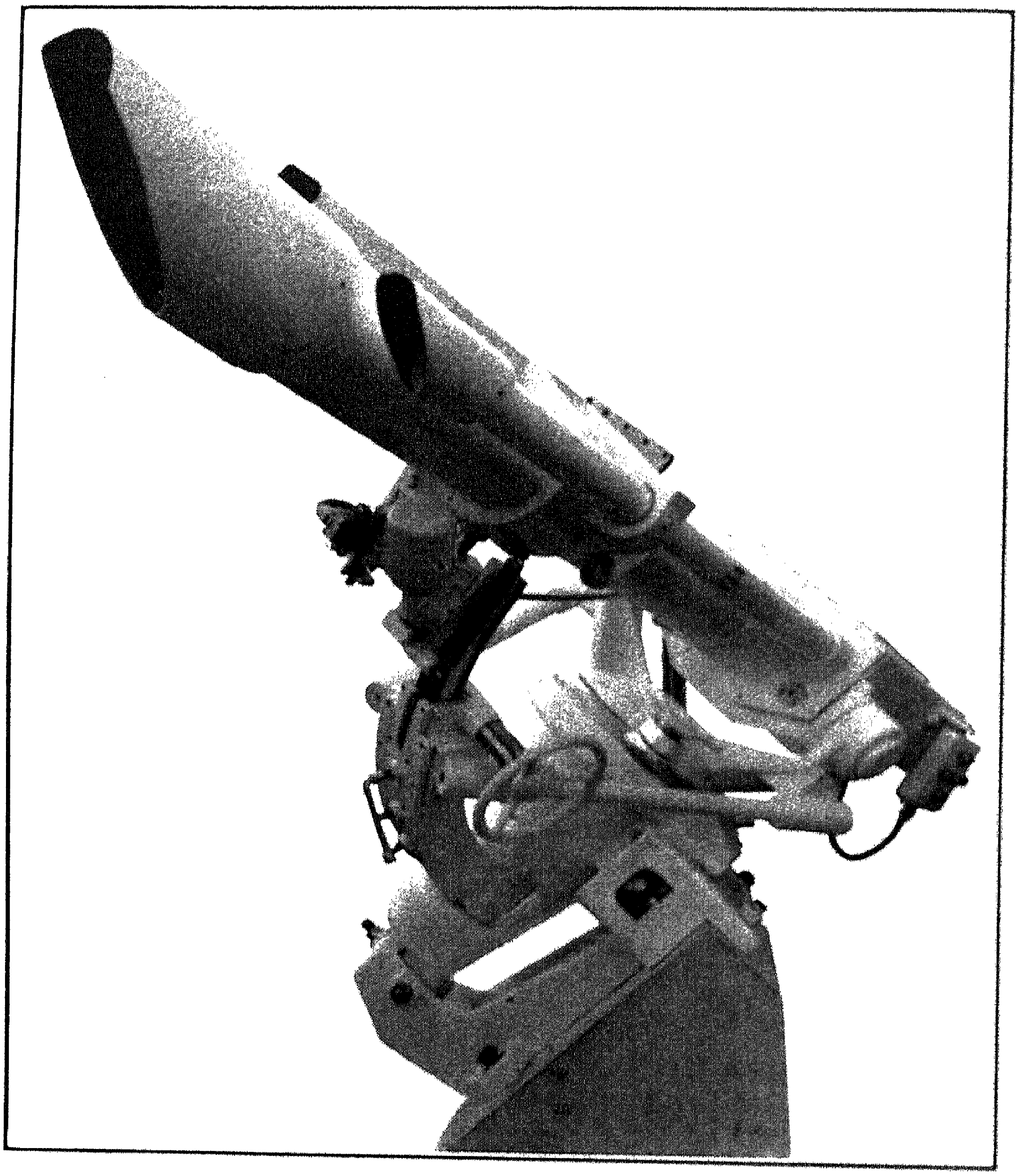

FIG. 1 — Lyot heliograph of Meudon, adopted as the prototype for the flare-patrol instrument

of the Sun on the slit of a spectrograph or other instruments near ground level. This arrangement has proved to be one of the most convenient and productive forms of telescope for solar observation, allowing the use of very large accessories solidly mounted on stable piers. Its continued excellent reputation is indicated by the fact that the new solar equipment of the Crimean Astrophysical Observatory is built around a solar tower.

In spite of its great advantages the solar tower has one fault which precludes its use for the most delicate observations at the solar limb. The unavoidable flat mirrors are incorrigible light scatterers. The scattered light is not excessive and does not appreciably affect observations of the phenomena of the solar disk, but it is quite sufficient to submerge the corona completely in a bright instrumental background, and increases the difficulties in prominence observation.

Lyot coronagraph. For work at the limb the coronagraph is unsurpassed. It was Lyot's solution to the long-standing problem of observing the corona without the benefit of an eclipse. The problem is to see the corona immediately adjacent to the disk of the Sun which is roughly a million times brighter. The observer is faced with a difficulty analogous to that of seeing the license plate of an oncoming car on a foggy night in the face of a pair of glaring headlights. The atmosphere of the Earth scatters light into a halo surrounding the Sun. At most sea-level locations this halo is normally more than a thou-

sand times as bright as the corona, and quite completely hides it. The history of efforts to see the corona without an eclipse is mainly the search for locations where the atmospheric halo is greatly reduced. Such sites were found, where the halo was at times less than ten millionths of the surface brightness of the Sun, but the corona remained invisible. It was then realized that the atmosphere was not the only villain. The observing instrument itself scatters light from the solar disk in a diffuse haze over the entire field. A good refractor might scatter no more than one part in a thousand, but this is still a thousand times the brightness of the corona. In terms of our car-driving analogy, the scattering telescope is the equivalent of a dirty windshield between the observer and the headlights. The problem looked hopeless, and one eminent astronomer declared quite unequivocally that the corona could never be observed outside of eclipse. Almost simultaneously, in 1931, Lyot made the first such observations with his coronagraph.

The coronagraph [*Lyot*, 1939; *Evans*, 1953] is a highly specialized telescope ingeniously designed to eclipse the Sun artificially and reduce the scattered light from the solar disk to a minimum. Scatter originates in optical imperfections on the surfaces and in the material of the objective lens, and in the diffraction of light from the disk at the edge of the objective. Lyot used an objective consisting of a simple lens made of the most perfect glass obtainable and polished far beyond normal requirements (Fig. 2). The solar disk was eclipsed by an occulting disk in the focal plane of the objective. Diffracted light from the disk was trapped by forming an image of the edge of the objective with a field lens behind the occulting disk. Since the scatter appears to emanate from this edge it could be eliminated by diaphragming its image. A second image-forming lens behind the diaphragm reimaged the occulting disk and the surrounding corona in the final focal plane. Lyot's original design embodied all of the known scatter-reducing devices, and remains basically unchanged in all coronagraphs constructed since.

By itself the best coronagraph in the best location is still not sufficiently scatter-free to show the corona. Fortunately, the composition of coronal light differs from that of scattered light originating in the photosphere. It consists of emission lines and white light that is strongly polarized along the direction of the solar radius. Both of these characteristics permit us to discriminate between coronal and scattered light. In a spectrograph, the continuous scatter spectrum is diluted by a large factor, and the emission lines of the brighter parts of the corona stand out in strong contrast (Fig. 3). This spectroscopic method is by far the easiest and among the most useful forms of coronal observation. With somewhat more difficulty, the form of the emission-line corona can be photographed in detail through a birefringent filter with a two or three angstrom pass band centered on one of the stronger emission lines (Fig. 4), exactly as the prominences are photographed in light of the H-α line. The coronagraph for direct photography and the flare-patrol telescope at the Sacramento Peak Observatory are shown in Figure 5. Still more difficult is the detection of the polarized component of the white light of the corona. For this work a sensitive photoelectric polarimeter is attached to the coronagraph and the polarization of the light at the solar limb is charted. The sensitivity required approaches the attainable limit and the uncontrollable disturbances in polarization caused by the atmosphere are large. Fortunately the latter are systematically different from coronal polarization and can be largely eliminated.

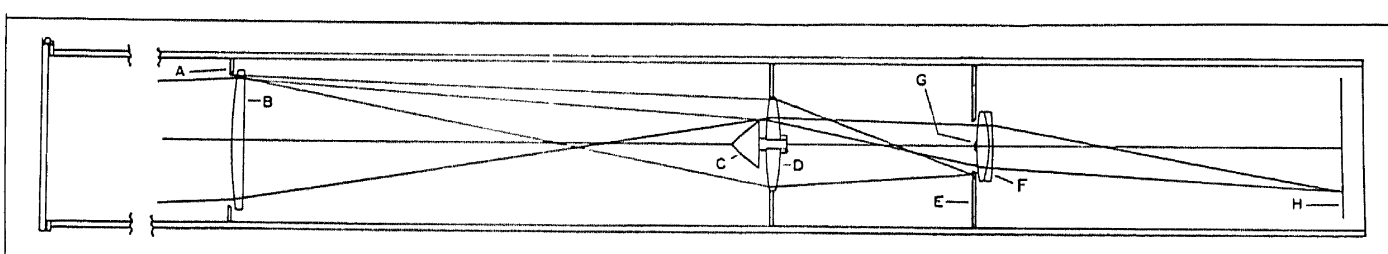

Fig. 2 — Diagram of Lyot coronagraph optical system; A, entrance diaphragm; B, simple lens objective; C, occulting disk; D, field lens; E, diaphragm to eliminate diffracted light; F, image forming lens; G, target to occult doubly reflected light in objective; H, final focal plane

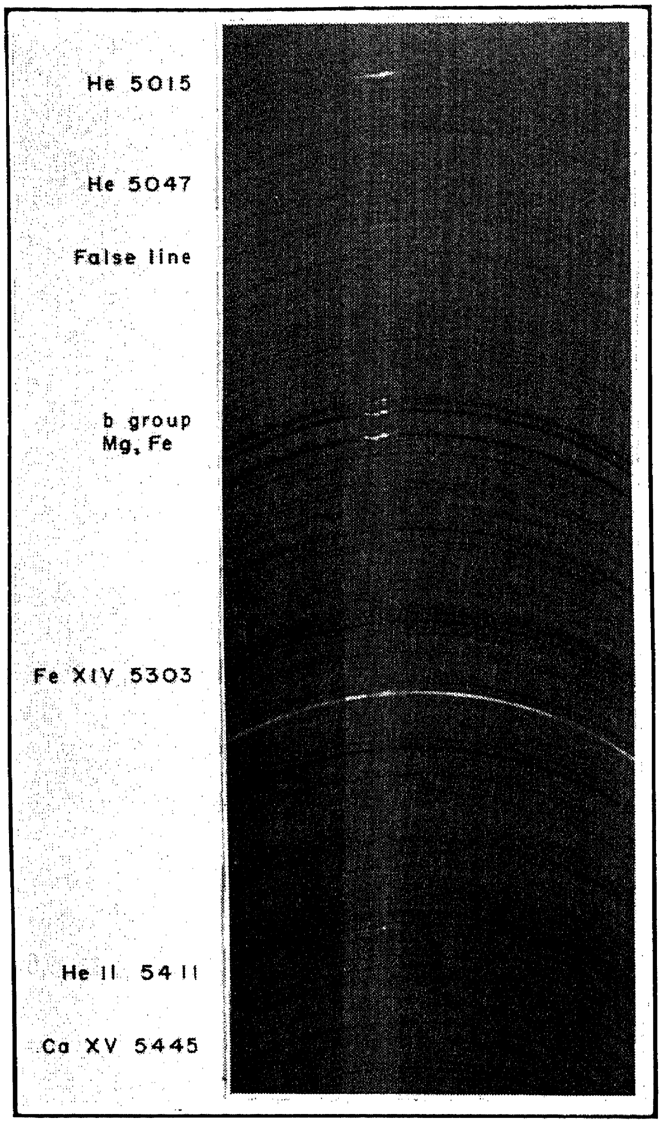

FIG. 3 — Spectrogram showing bright coronal and prominence lines, taken through a four-inch spectrocoronagraph

During the IGY spectrocoronagraphs operate at a dozen or more stations. The Sacramento Peak Observatory will continue to take motion pictures of the emission corona whenever sky conditions permit, and the High Altitude Observatory and possibly the Pic du Midi Observatory will make regular observations of the coronal polarized light.

Birefringent filter—Like the coronagraph, the birefringent filter [*Lyot*, 1944; *Evans*, 1953] has been in use for some years and can be regarded as a standard tool of solar astronomy; it was invented by Lyot in 1935. By an ingenious use of the interference of the fast and slow components of polarized light traversing birefringent crystals (usually quartz or calcite) a series of sharp widely spaced wave-length bands are transmitted, and the remainder of the spectrum is absorbed. The designer may choose the wave length of one transmission band, the band width, and, roughly, the separation of the adjacent bands in the spectrum. With a little ingenuity and some good luck he can design a filter with transmission bands coinciding with two or more lines of special interest. Lyot discovered a quite fortuitous basic design now widely used, which transmits no less than six lines of solar interest including Hα, λ 6374 of the corona, D3 of helium, λ 5303 of the corona, a magnesium line of the b group, and Hβ. 'Tunable' filters which can be adjusted to transmit any wave length are theoretically possible and have been designed, but they call for exceedingly complex mechanical adjustments and a considerable increase in optical complication. To the best of my knowledge, no fully tunable filters have yet been made. Most of the filters now in use have transmission

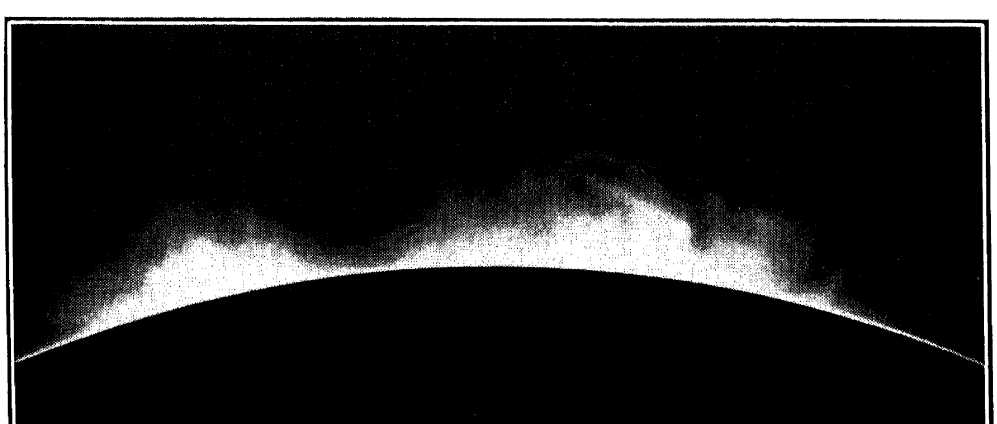

FIG. 4 — Solar corona photographed through a combination of six-inch coronagraph and birefringent filter in light of λ 5303 of FeXIV

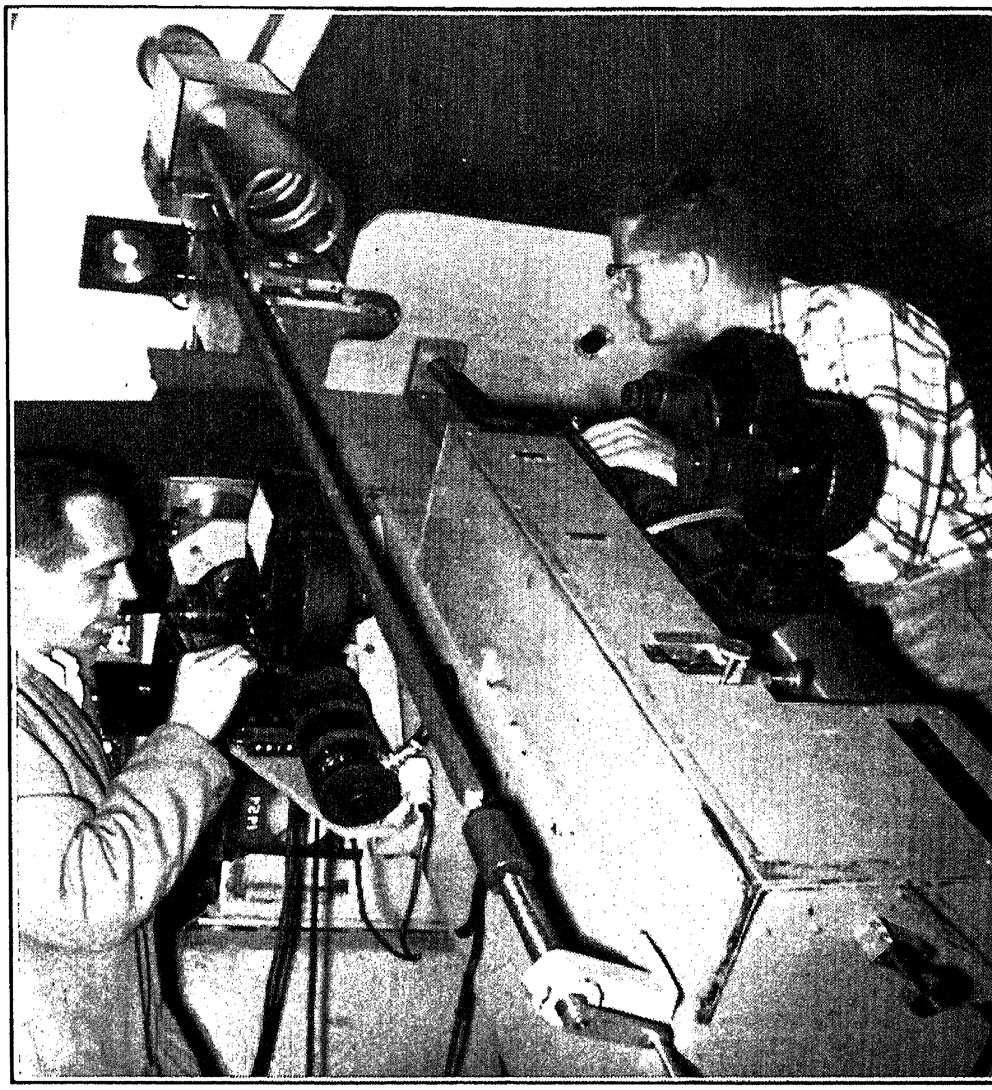

FIG. 5 — Six-inch coronagraph with birefringent filter (top) and flare-patrol heliograph (east side) carried on a single mounting; a four-inch spectrocoronagraph is carried on the west side of the spar

bands centered on Hα, with an effective width from 0.5 to 5 angstrom units.

A birefringent filter is constructed in the form of a multiple sandwich of alternating layers of polaroid film and birefringent crystals. The optical retardations (thickness multiplied by the birefringence) of the crystal layers form a geometric progression in powers of 2, and a 1 A filter would normally require six or seven elements of quartz and two of calcite, with a total length of about 20 cm.

Many solar features radiate or absorb selectively in particular lines of the spectrum and can be seen only by isolating or tuning on these lines. Their observation is analogous to the reception of a radio station on a particular frequency. A radio which accepted all frequencies simultaneously would be quite useless, since all stations and all static would come in at once. The purpose of the birefringent filter is to tune on the wave length emitted by the solar feature under observation and to eliminate the static composed of white light, which would otherwise drown the object out. It performs the function of a spectroheliograph in the photography of disk phenomena (Fig. 6) like flares, plages, filaments, and prominences at the limb (Fig. 7). It generally gives better definition and is much faster, but lacks the flexibility of the spectroheliograph in the choice of band width and wave length. Although it is a complicated little device, the filter is compact and reliable, qualities which admirably fit it for use with modest telescopes and by comparatively unskilled operators. The flare-patrol network for IGY, for instance, would hardly be feasible without it. Combined with the coronagraph, it is the ideal instrument for observing prominences, and the only device

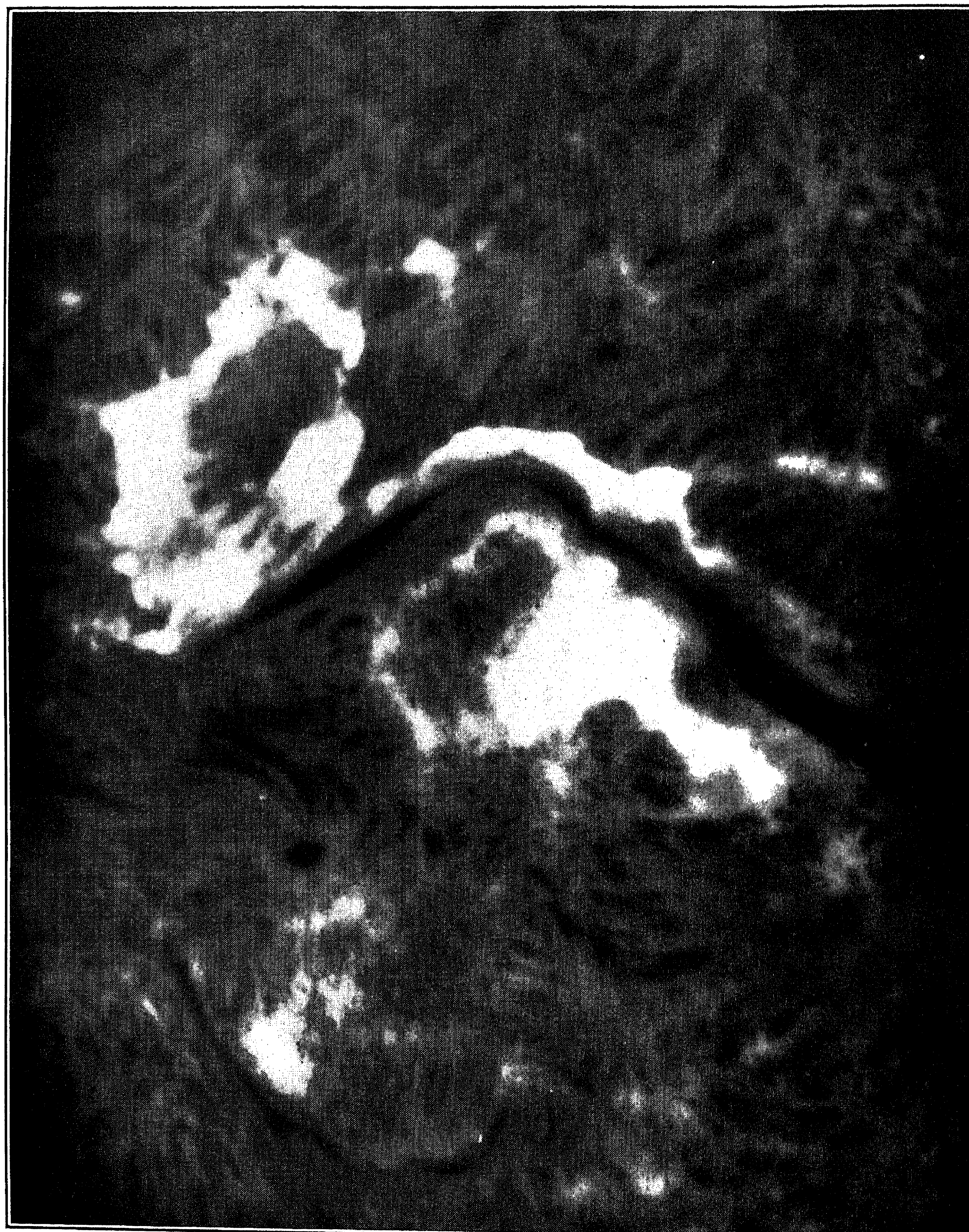

FIG. 6 — Photograph of the solar disk in an active region, on large scale; this was taken with the 16-inch coronagraph of the Sacramento Peak Observatory through an H-alpha birefringent filter of 0.65 angstrom pass band

FIG. 7 — Solar prominence photographed through a birefringent filter in H-alpha light

available for direct photography of the emission corona.

Roberts [1957] estimates that at least 50 filters with pass bands of 1 A or less are now in use, 10 or 15 of them in the USSR. Most of these will contribute in some measure to the IGY observations of solar activity.

A new type of birefringent filter has been developed during the last three or four years by Solc in Czechoslovakia. It is simpler than the Lyot type in having crystal elements all of the same thickness, but more complicated in that there are a great many more of them. The most attractive feature, however, is that only two polarizers are required; the transmission of the filter must therefore be very high. Although prominence photographs have been obtained with these filters, the optical theory has not yet been fully worked out, and it is not certain that they are suitable for the much more exacting task of showing monochromatic details on the disk of the Sun. At present we cannot look to the Solc filters for a large contribution of solar observations during IGY.

Spectroscopes—The most fundamental of all the instruments of solar research is the combination of telescope and spectrograph. Solar spectroscopy began with the identification of the chemical elements in the solar atmosphere. We now accept this as a matter of course, but the astronomers of the 1860's must have reveled in the unexpected and undreamed of power of the new tool that came so suddenly into their hands with the discovery of the laws of spectrum analysis. Modern astrophysics dates from that time, and the central importance of spectroscopy has steadily grown since its inception. The demand for more and more powerful spectroscopic equipment has kept pace with the increased knowledge of the significance of fine detail in the spectrum, and the end is not in sight. In the present state of the art, the most important observational task of solar spectroscopy is the accurate measurement of the profiles of the absorption and emission lines of the disk, chromosphere, prominences, and corona. The most powerful instruments of today are adequate to provide plenty of food for theoretical ruminations, but the theoreticians are never fully satisfied and would welcome still more spectroscopic power.

In solar research, power is a complicated function of spectroscopic resolution, purity of spectrum, and speed, in combinations which vary widely with the problem in hand. Whatever the combination, however, the ultimate limiting factor is inevitably the dispersing element of the spectrograph, which usually means a grating. All the other components of the optical system can be made better than the grating by quite routine

optical shop procedures, but the ruling of a good grating is a fantastically difficult mechanical problem, which has been solved in only a few laboratories in the world.

Diffraction gratings—Briefly stated, the problem is to rule 15,000 grooves per inch in a metal surface over the greatest possible distance [*Harrison*, 1949]. This in itself would be a stiff job for an ordinary instrument shop, but it is only the beginning of the problem. In order to achieve anything approaching theoretically perfect resolving power and freedom from scattered light, comparable with that of a quite ordinary lens, the spacings of the grooves must be uniform. Periodic errors accumulating to more than a tenth of the wave length of the light (about two millionths of an inch) with a root mean square accidental error of more than a twentieth of a wave length are intolerable. Anyone who has required mechanical work with tolerances of less than one ten-thousandth of an inch will have some conception of the magnitude of the difficulties. Ruling engines are inherently perverse mechanisms which creep and bend, and expand and contract perhaps a hundred times the permissible ruling tolerances. Harrison has likened the problem of ruling to that of painting a miniature portrait with a whitewash brush insecurely attached to a six-foot length of rubber hose for a handle. Matters are further complicated by the need for a very definite groove shape with flat sides at rigidly specified angles. This is the condition for high light efficiency, an item of the utmost importance even for the observation of an object as bright as the solar photosphere.

In view of all these obstacles, the magnificent six- and eight-inch gratings produced during the last few years by Babcock at Mt. Wilson, Strong at Johns Hopkins, and the Bausch and Lomb Optical Company rank as true prodigies of mechanical art, and we hear of comparable gratings being made in Russia. In resolution they are hardly distinguishable from theoretical perfection, and scattered light has been reduced to negligible levels.

These grating are now the basic elements in at least six new solar spectrographs ranging in size from the high resolution 50-ft vacuum spectrograph fed by the McGregor tower telescope of the McMath-Hulbert Observatory, to the elegant little five-foot coronal spectrograph at the Climax Station of the High Altitude Observatory. The improvement of these instruments over pre-war spectrographs represents a near discontinuity of power, and the impact on the study of solar activity in the next few years will be enormous. Further increases in the power of gratings can be expected in the next few years, as Harrison at MIT develops his interferometric ruling engines for the production of still larger gratings to standards of quality fully as rigorous as or better than those already attained. The first experimental eight-inch Harrison grating to be used in solar research has just been mounted in the 43-ft spectrograph at the Sacramento Peak Observatory, and is now undergoing its first tests in service.

Solar radio-noise observations—The introduction of radio observation in astronomy [*Pawsey* and *Smerd*, 1953; *Wild*, 1953] resembles the inception of spectroscopy, in that it provides a new and significant form of data of a nature entirely different from anything available before, adding a new dimension to our description of the universe. It is as though we had suddenly acquired a new sense. We are still in the exciting process of early exploitation, the skimming of the cream of fundamental knowledge opened up by a new and powerful technique. Although we can be certain that the radio observation of the Sun during future sunspot maxima will far surpass the present efforts, it is impossible to exaggerate the significance of the present work for the aims of IGY. The generation of radio noise is basically a simpler process than the emission of light, and the measurements can be much more readily interpreted. Furthermore, the tremendous observable frequency range of four decades, from 15 to 15,000 mc, provides the means for the study of physical conditions in the optically difficult regions extending from the photosphere out through the corona. This region is the only observable part of the Sun where the temperature reaches a million or more degrees, and much of the radiation that affects the terrestrial atmosphere must originate in it. In general, the height of origin of the radio waves increases with the wave length. Thus an analysis of the radio spectrum is an analysis in height in the solar atmosphere.

Compared to the optical refinements, radio observations of the Sun are rather crude. Usually the integrated radiation from the whole

solar disk is measured at some well-defined frequency. Measurements of this sort in light would yield no useful information on solar activity, since the total enhancement of light caused by an active region is too small to detect. Matters are very different at radio frequencies, however. Here the contribution of a temporary activity may be thousands of times the steady-state radiation from the whole disk, and the simple measurement of the integrated energy is very significant.

This fact has led to the establishment of a world-wide network of 200 mc radiometers similar to the flare-patrol network. In fact, many of the stations are the same. The stations are well distributed in longitude and are now keeping the Sun under a 24-hour-a-day watch. Like the flare patrol, the establishment of a 200 mc radiometer requires a relatively modest outlay in money and manpower. Enthusiasm for the project is high, promising thorough coverage and important results.

In a sense the 200 mc patrol is a speculation, because at present the true significance of the radio-noise outbursts at this frequency is not really understood. There can be no doubt about the soundness of the speculation, however. Any local phenomenon with an output of any form of radiation which exceeds that of the whole steady-state Sun is sure to be important and deserves most careful attention.

The present development in solar radio astronomy is directed toward two goals. They are the recording of the radio spectrum over broad bands of frequency, and the increase of resolving power at a fixed frequency to determine the positions of radio sources on the solar disk. Excellent progress in both fields has been made, and the logical next step, the combination of the two, is in the thinking stage.

Radio spectrometers—The electronic problem of sweeping the spectrum was brilliantly solved by Wild in Australia, who first determined the time-frequency variations of outbursts from 60 to 130 mc in 1950. The instrumental difficulties are formidable and radio spectrometers have been slow to appear at other observatories. However, several are in the process of construction, at University of Michigan, at the Institute for Theoretical Astrophysics in Norway, at Meudon, and at the Crimean Astrophysical Observatory, and will probably be operating before the end of IGY. At present the only ones taking continuous observations are Wild's instrument in Australia and the excellent Fort Davis, Texas, spectrometer of the Harvard College Observatory, which sweeps the range from 100 to 600 mc three times per second. The results from both these instruments during the present sunspot maximum are very exciting and puzzling, indicating solar radio disturbances which rise with velocities of the order of 500 km/sec through the corona and occasionally appear to return downward with comparable speed. A quite separate event appears to be a disturbance which shoots out at 10,000 or more km/sec, possibly associated with the emission of cosmic rays from the Sun.

Radio interferometers—Directional resolution, by means of which the positions of radio sources are located on the Sun, is achieved by the use of radio interferometers, which are rather exact analogies of optical interferometers. Angular resolution is simply the angle subtended by one wave length at a distance equal to the total aperture. Since useful resolution is about 0.001 radian (one tenth the solar diameter), the required antenna array must be about 1000 wave lengths across. Some of the most interesting activity occurs at wave lengths greater than one meter, calling for an array of the order of one kilometer wide. Matters are further complicated by the need for resolution in two dimensions. It is not surprising, therefore, that rather few observatories have had the resources for high-resolution radio work. Several very effective one-dimensional interferometers are in use, however, and at least one two-dimensional interferometer, a Mills Cross, is being set up at Stanford by Bracewell. Since the latter instrument may not be completed until near the end of IGY, the radio interferometer coverage of the Sun will not be entirely satisfactory, but the results from existing equipment will add tremendously to the value of both the 200 mc and the spectrometer observations.

Other instruments—Although I have been able to skim only the most basic of the instruments for solar observation during IGY, there are many others which are perhaps less imposing but which can be expected to yield very substantial results. Photometric devices for photoelectric, photographic, and visual measurements of light intensities, devices for the rapid determination

of velocities across and along the line of sight, the solar magnetograph of the Babcocks, and rapid data reducing systems like direct intensity recording microphotometers and isophotometers, to name a few, will make most important contributions.

Significance of the program—All of the instruments described are only tools which will provide data for the intellectual activity of interpretation, from which new knowledge will flow. By themselves participating institutions could doubtless use their equipment to good effect. But the important ingredient of the IGY is a form of cooperation which will multiply the results far beyond the number of institutions involved. As far as possible all observable features of a given solar event and the geophysical responses will be observed simultaneously at the different stations. Of course the exigencies of weather and instrumental readiness will interfere with the securing of a really complete picture in many cases, but if only a few outstanding events are thoroughly covered, the results more than justify the effort. This is the immediate purpose of IGY, and solar astronomers everywhere welcome the opportunity to participate and benefit from a scientific cooperative effort on a scale they have never experienced before.

References

EVANS, J. W., The coronagraph, *The Sun,* G. P. Kuiper (ed.), Univ. Chicago Press, pp. 635–643, 1953.

EVANS, J. W., Birefringent filters, *The Sun,* G. P. Kuiper (ed.), Univ. Chicago Press, pp. 626–634, 1953.

HARRISON, G. R., Production of diffraction gratings, I, development of the ruling art, *J. Opt. Soc. Amer.,* 39, 413, 1949.

LYOT, B., The study of the solar corona and prominences without eclipses, *Mon. Not. R. Astron. Soc.,* 99, 580, 1939.

LYOT, B., Le filtre monochromatique polarisant, *Ann. d'Astrophysique,* 1, 31, 1944.

MCMATH, ROBERT R., Tower telescopes and accessories, *The Sun,* G. P. Kuiper (ed.), Univ. Chicago Press, pp. 605–626, 1953.

PAWSEY, J. L., AND S. F. SMERD, Solar radio emission, *The Sun,* G. P. Kuiper (ed.), Univ. Chicago Press, pp. 466–531, 1953.

ROBERTS, W. O., *Ninth Report of the Commission for Study of Solar Terrestrial Relationships,* Int. Council Sci. Unions, 1957.

WILD, J. P., Techniques for observation of radio-frequency radiation from the Sun, *The Sun,* G. P. Kuiper (ed.), Univ. Chicago Press, pp. 676–692, 1953.

Sacramento Peak Observatory, Geophysics Research Directorate, AF Cambridge Research Center, Sunspot, New Mexico

Whistler Studies at Dartmouth College

Millett G. Morgan

Introduction—The broad program of synoptic observation of whistlers which the United States has undertaken for IGY, had its beginning in 1952 in Sydney, Australia, at the Tenth General Assembly of the International Scientific Radio Union. J. A. Ratcliffe reported there on the recent work of one of his doctoral candidates at Cambridge University. What Ratcliffe had to report was exciting to the imagination and "not something one quite dared accept." R. A. Helliwell of Stanford University, H. E. Dinger of the Naval Research Laboratory, and the author, each heard this presentation and reacted in somewhat similar fashion: What an ideal object of basic research combining interest in radio wave propagation, geophysics, and solar-terrestrial relationships! Each of us has been amply rewarded in the five years which have passed since that time. At Dartmouth we were engaged in high-frequency studies for the U. S. Navy Bureau of Ships and it was by their indulgence that we got started.

Whistlers are audio-frequency radio waves arising from lightning flashes. To hear them, one need only apply the electric or magnetic field of the wave to an electro-mechanical transducer, such as a headphone, to convert the electromagnetic signal to a sound wave. Of course amplification is usually needed, but I have heard them on our telephone at home, picked up on five miles of two-wire open line. Supplying amplification usually leads to trouble: oscillation and interference from harmonics of the power-line frequency. Once these matters are overcome, and an antenna of suitable size and match to the amplifier is arranged, whistlers will be heard virtually every day in the geomagnetic latitude belt 45–55° north or south.

Ratcliffe's graduate student, *Storey* [1953] (now with the Canadian Defence Research Board in Ottawa), extended the theoretical work of Eckersley, done fifteen years earlier, and combined it with extensive experimental observations. Storey deduced that whistlers result from the propagation of the very low frequency energy radiated by a lightning flash, along the flux of the Earth's magnetic field far above the Earth and down again to the symmetrical point in the opposite hemisphere, taking a second or two to make this very long trip. The lower frequencies travel slower than the high so that the original impulse is spread out into a swish or whistle of descending pitch when it is received. Storey's support for this thesis was very strong except that, for the guiding to be maintained thousands of miles above the Earth so that the wave would not escape, a minimum electron density of about 400 electrons/cc is required. Our knowledge of the rate at which the atmospheric density lapses with height is very limited, but an extension to so great a height would leave nothing like 400 particles/cc.

When the publication of Storey's work was in proof, the results of a photoelectric study of the zodiacal light came to his attention. This is the sunlight that is scattered into the dark hemisphere. It is called zodiacal because it is concentrated in the ecliptic plane. From their observations, the authors of this work had deduced that 600 electrons/cc were present to produce the observed scattering. Of course this independent deduction strengthened Storey's case.

Simultaneous observations at Hanover, N. H., and Washington, D. C.—By early 1955, the three of us in America who had been working with whistlers since hearing about them in Sydney, were beginning to get results. In order not to miss any periods of good activity, I had introduced the whistler receiver into our household and had my wife wearing earphones as she went about her household duties. One of our best records was obtained when one of our daughters (then 6) woke us up early Sunday morning because there were "wonderful whistlers" coming in. In March of that year, there was outstanding activity, and Dinger and I obtained some very good simultaneous observations. Analysis of the records showed that the characteristics of individual whistlers heard in Hanover and Washington were identical [*Morgan* and *Dinger*, 1956].

Conjugate point experiment—What was needed to clinch matters, was the setting up of suitably placed stations in the northern and southern

hemispheres to make simultaneous observations, and we set about in 1955 to perform such an experiment. Starting from a point in the northern hemisphere where whistlers are observed, and following the flux of the Earth's magnetic field to the southern hemisphere, one invariably lands in the ocean. Going at it the other way around, one again lands in the ocean or on land physically inaccessible. Since the exercise in spherical trigonometry required for each try is rather tedious, we scribed a set of geomagnetic coordinates on a globe to see where the best possibilities lay and then performed calculations to place the stations accurately. In this manner, sites in the Aleutian Islands and New Zealand were selected.

By a fortuitous circumstance, G. McK. Allcock (New Zealand Dominion Physical Laboratory) was thinking along similar lines at the same time although he had not selected a path. With his cooperation, the experiment was performed in August and September 1955. H. W. Curtis of Dartmouth went to Unalaska where the U. S. Army Signal Corps made facilities available to us. After about a week of operation, the observers heard whistler trains; that is a whistler followed by a train of echoes. Independently they sent one another cable messages which crossed in the mail. The messages contained times of occurrence which made it very clear that corresponding signals had been heard at both ends of the path. Subsequent spectrographic analysis revealed that the details of Storey's postulates had been proven, including his most tenuous one: that there can be as many as 400 electrons/cc thousands of miles above the Earth [*Morgan* and *Allcock,* 1956].

Arctic observations—We commenced observations in the auroral zone at Knob Lake, Quebec, in 1955. In the summer of 1956, Curtis made observations at higher latitudes at Frobisher Bay (Baffin Island), at Søndre Strømfjord, Greenland, and on the Greenland Icecap east of Thule. Weak whistlers are occasionally heard at Knob Lake but none were heard at any of the places which Curtis visited inside auroral zone.

The dawn chorus is observed at Hanover and Knob Lake, and was heard by Curtis at Frobisher Bay and Søndre Strømfjord but not at Thule. This phenomenon is believed to be a vlf emission produced by the precipitation of solar particles upon the outer atmosphere. R. M. Gallet of the National Bureau of Standards and R. A. Helliwell have put forth a theory of the generating mechanism which is having growing success in explaining the various vlf emission phenomena which are observed.

Multiple whistlers—We have continued the Unalaska station in routine operation since its original installation. The whistler activity there is very high. The whistlers are predominantly of the short or one-way type; that is, they originate in the opposite hemisphere. It is not uncommon to have a lightning flash produce two or more separate whistlers. Usually the multiple whistlers are closely spaced in arrival time. Because the spacing within successive groups is constant during a given period of activity, it is concluded that this is certainly due to the existence of separate propagation paths.

In analyzing an Unalaska record taken on Nov. 11, 1956, I was unable to account for the details of an echo train. Curtis pointed out that the first two whistlers were unusually widespread multiples and that the succeeding echoes could be explained by successive propagation over these paths in various sequential combinations. One of the original pair was stronger than the other and from this he inferred that its path had the smaller attenuation and would be preferred in the echoes. The record showed this to be true.

Visual observation of lightning and whistlers—After many failures, we have recently been fully successful in correlating visual observation of lightning with whistlers. On May 27, 1957, I observed a period of an hour or more in which visible lightning and audible thunder were occurring, with every flash producing a strong whistler with echoes. There had been an unelucidated report of such an observation years ago, but since many attempts by Dinger and ourselves over a period of several years had been totally unsuccessful until now, this was a very significant experience.

Visual observation of aurora and vlf emissions—With the knowledge that vlf emissions and aurora are both strongly correlated with geomagnetic disturbance, it is reasonable to seek a direct correspondence between vlf emissions and visible features in the aurora. Storey and I have both sought this without success. However, my wife has detected a correlation which she and I now find in every notable display of

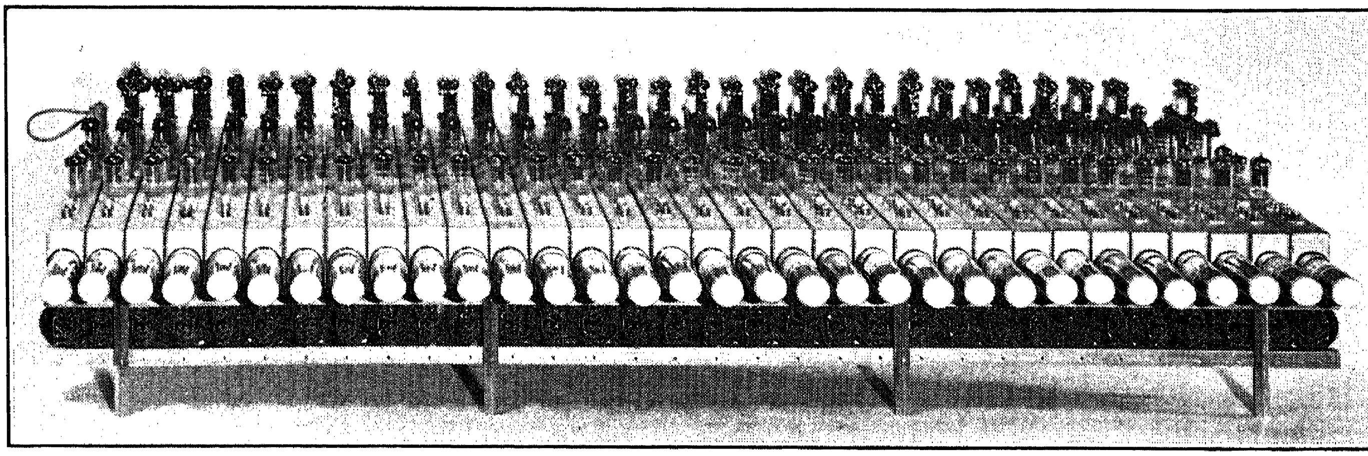

FIG. 1 — Audio-frequency spectrum analyzer for whistlers; a 32-channel spectrograph presenting the output of each channel on a one-inch cathode-ray tube has been developed at Dartmouth College for the rapid analysis of whistler data recorded during IGY; records are produced on continuously moving 35 mm photographic film on which the image of the row of tubes is focused; the instrument was developed by H. W. Curtis of the Thayer School of Engineering at Dartmouth

flaming auroral rays. The observation appears to be consistent with the Gallet-Helliwell theory of vlf emissions.

The solar flare of February 23, 1956—In the daytime, very low frequency radio waves are reflected from the ionosphere at a height of about 70 km. At night, the ionization at that level disappears rapidly and the reflection height rises to about 90 km. The daytime absorption of the waves is much greater because the detached electrons, which are set in motion by the electric field of the radio wave, make more collisions with air molecules in the denser atmosphere at the lower level.

At night, when the ionospheric absorption is low, the very low frequency radio pulses from lightning discharges bounce back and forth many times between the Earth and the ionosphere. This imparts a musical character to them and they are called 'tweeks.' Tweeks last somewhat less than a tenth of a second. They descend rapidly in frequency to a limiting lower value determined by the ionospheric reflection height.

On rare occasions, solar flares produce strong cosmic-ray bursts, and ionospheric effects on the dark hemisphere of the Earth. The flare of February 23, 1956, was such an event and the results were noted at many observatories. Daytime propagation conditions for very low frequency waves were suddenly manifest in the dark hemisphere. At the suggestion of J. M. Watts of the National Bureau of Standards, we analyzed our records of tweeks for that period and substantiated the findings of others deduced from radio transmission circuits.

IGY preparations—Routine whistler data recorded every three hours at Unalaska; Dunedin and Wellington, N. Z.; Knob Lake, Que., Canada; Hanover, N. H.; Washington, D. C.; and Gainesville, Fla.; have been collated at Dartmouth and exchanged with many stations. An agreement has recently been reached insuring that all participants in the coordinated western hemisphere group recording whistlers during IGY, will use a uniform reporting sheet for the daily log of aural monitoring of the tapes. To provide guidance and insure standardization for all countries participating in IGY programs, the Special Committee for IGY (CSAGI) arranged for the preparation of manuals in each field. The author prepared the manual on whistlers and dawn chorus.

We have undertaken responsibility for a chain of thirteen stations, from the Arctic to the Antarctic, for IGY. We will continue our Aleutian – New Zealand observations on a limited scale as an experiment outside the synoptic program.

Equipment—In addition to refinement of the whistler receiving equipment, automatic programming and recording equipment has been designed. This provides timing to 0.05-sec accuracy so that events recorded simultaneously at widely separated stations can be identified and correlated.

Because of the varying quality of radio reception of time signals on a continuous basis, it was recognized that the maintenance of a local-station standard is essential. A standard which does not require adjustment more than about

twice a month has been adopted. By placing time marks on the magnetic recording tape, reliance upon constant tape transport speed is eliminated. The calibration of the overall system sensitivity is automatically recorded on each schedule.

Curtis has undertaken the development of a multi-channel audio-frequency spectrum analyzer for the rapid analysis of data (Fig. 1). Records are produced on continuously moving 35 mm photographic film on which the image of the row of 32 small cathode-ray tubes is focused.

References

Morgan, M. G., and H. E. Dinger, Observations of whistling atmospherics at geomagnetically conjugate points, *Nature*, 177, 29–30, 1956.

Morgan, M. G., and G. McK. Allcock, Observations of whistling atmospherics at geomagnetically conjugate points, *Nature*, 177, 30–31, 1956.

Storey, L. R. O., An investigation of whistling atmospherics, *Phil. Trans. R. Soc.*, **246**, 113–141, 1953.

Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire

Whistlers and Very Low Frequency Emissions

R. A. Helliwell

Introduction—The exosphere, an enormous region of nearly empty space beyond the regular ionospheric layers, is the subject of a unique program of radio measurements to be carried on by the IGY Panel on Ionospheric Physics. A remarkable class of naturally occurring radio waves is used to measure the density of ionization and other characteristics in this little-known region surrounding the Earth. The signals to be used are known as 'whistlers and vlf emissions' and are of unusually low frequency, ranging from less than 1000 cycles to more than 30,000 cycles. They can be heard with the aid of an ordinary audio amplifier connected to a large antenna. Those called whistlers, long descending whistles lasting one to three seconds, are produced by the dispersion of energy from lightning discharges. Those classed as vlf emissions appear to be generated somewhere in the exosphere, but the mechanism is still uncertain. (The term 'vlf emissions' was first proposed by R. M. Gallet of the National Bureau of Standards. These together with whistlers come under the more general classification of atmospherics. Those atmospherics which are propagated by means of the ground wave or by reflection from the ionosphere are often referred to as sferics. One particular form known as a tweek has a somewhat musical sound resulting from a long train of pulses produced by different numbers of reflections between Earth and ionosphere. An unusually long tweek (50–100 milliseconds) may sometimes be mistaken for a whistler.) They include warbling and chirping sounds known as chorus, risers, hooks, hiss, and various more complicated signals.

The property that makes these odd-sounding signals so interesting and potentially useful is that their paths through space are bound to the curved lines of force of the Earth's magnetic field through the action of hitherto unsuspected quantities of ionization. These flux-line paths may extend as far as 30,000 mi beyond the surface of the Earth into regions virtually inaccessible by any other means presently at hand. Their general nature is shown in Figure 1, which is a plot of the dipole field of the Earth for every ten degrees of geomagnetic latitude. The dotted area close to the earth represents the known regions (E and F2 layers) of the iono-

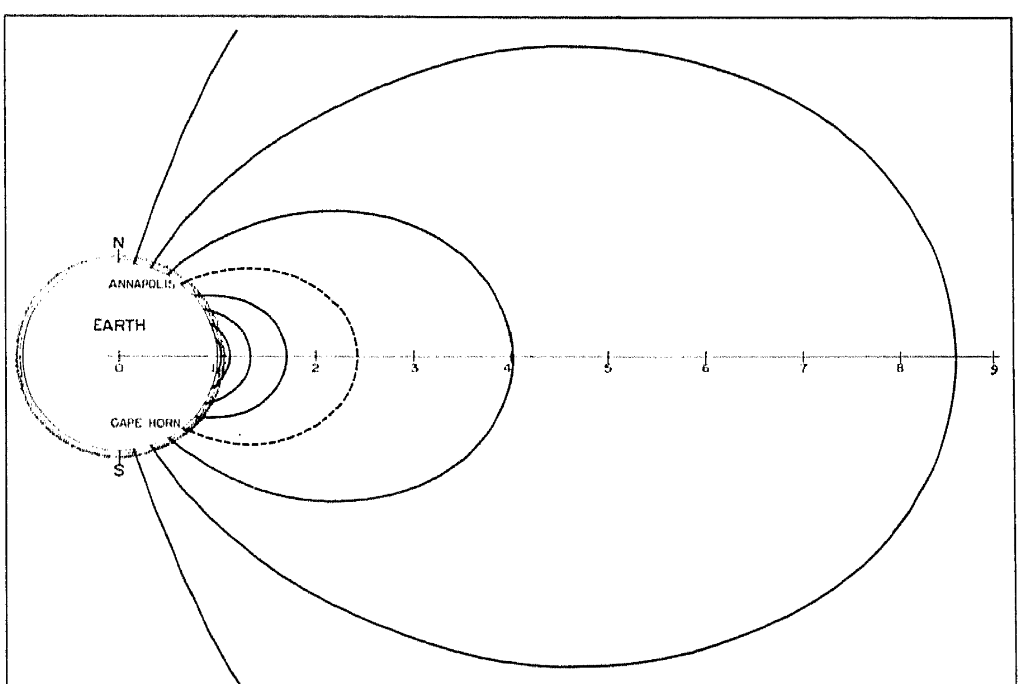

Fig. 1 — Lines of Earth's dipole magnetic field for each ten degrees of geomagnetic latitude; dotted area represents the known ionosphere; dashed line is assumed path of NSS echoes

sphere which, it is easily seen, contain only a small fraction of each flux-line path with the exception of those close to the equator.

Why is such a near-void as the exosphere so important? The reason is that it is a vital link between events occurring on the Sun and subsequent effects in the Earth's atmosphere. It is in the exosphere that streams of ionized gases generated during periods of sunspot activity are deflected by the Earth's magnetic field. The resulting motions of these ionized particles set up currents which are believed to cause the magnetic field variations known as magnetic storms. Penetration of the solar streams into the Earth's ionosphere causes auroras, disrupts radio communications, and may even affect large-scale weather phenomena. The mechanism by which these solar outbursts produce their profound effects is still uncertain; new knowledge of the exosphere is almost certain to be of help in reaching an understanding of these puzzling phenomena. Whistlers and vlf emissions offer intriguing possibilities for calculating the distribution of free charge in the exosphere, for exploring the far reaches of the Earth's magnetic field, and for measuring the velocities and densities of solar corpuscular streams. Knowledge of these phenomena obtained during IGY will have an important bearing on studies coming under other IGY disciplines such as solar activity, aurora and airglow, geomagnetism and cosmic rays.

During the IGY more than thirty specially designed recorders, spread widely over the Earth's surface, capture the electrical 'sounds' of whistlers and vlf emissions automatically. At precisely 35 minutes past each hour, synchronized electronic clocks start the tape recorders which then record any incoming signals for a period of two minutes. Shortly after recording, the tapes are monitored by ear, and logs are made of their contents. Summaries of occurrence statistics are prepared for correlation with other IGY data. Most of the tapes will be preserved for later quantitative spectrum analysis.

Historical Background

Our subject began, oddly enough, while the German scientist Barkhausen was eavesdropping on Allied telephone conversations during World War I. Using a sensitive audio amplifier connected to a pair of separated ground rods, he frequently heard many whistling sounds of descending pitch, each lasting one second or more. He recognized these as a new natural phenomenon, to which he gave the name whistler [*Barkhausen*, 1919]. *Eckersley* [1928] and his co-workers of the Marconi Company reported a positive correlation between whistler occurrence and solar activity. They made the important observation that whistlers frequently occur in trains preceded by a loud click, with a spacing of about three seconds between click and the first whistler and between whistlers of the train. *Eckersley* [1931] reported a nighttime observation by Tremellen during a summer thunderstorm in which every visible flash was followed by a whistler. This was the first direct evidence that whistlers were produced by ordinary lightning. (A. Glenn Jean at Boulder, Colorado, has reported, privately, that on a morning in April 1955 he saw several cloud-to-ground strokes each of which was followed by a whistler.) The Marconi workers also discovered another type of atmospheric which sounded like the warbling of birds at dawn. This they called the 'dawn chorus'; it is discussed later on in this paper.

Using the newly developed Appleton-Hartree magneto-ionic theory, *Eckersley* [1935] derived a dispersion equation which explained the whistler's descending pitch. He assumed loss-less propagation entirely along the direction of the Earth's field and that the wave frequency was small compared with the plasma frequency and gyrofrequency. In this case the group velocity is given by

$$v_g = 2c f_H^{\frac{1}{2}} f^{\frac{1}{2}} / f_0$$

where

c = velocity of light
f = wave frequency
f_H = gyrofrequency (proportional to strength of Earth's field)
f_0 = plasma frequency (proportional to square root of electron density)

The first quantitative measurement of frequency variation was made by *Burton* and *Boardman* [1933] in the United States from recordings taken in Ireland. They published a frequency time curve of two overlapping whistlers known as a whistler 'pair.' Eckersley analyzed these data and found that their results confirmed his dispersion theory which required the whistler frequency to be proportional to the

reciprocal of the square of time after the initial impulse.

Although the source and shape of the whistler were now explained, the problem of the path followed by the whistler was still a mystery. The path hypothesis which is the basis of the present IGY program was developed relatively by *Storey* [1953]. He showed, with both theoretical arguments and new experimental data, that some of the electromagnetic energy from a lightning discharge penetrates the ionosphere and guided by the lines of force of the Earth's magnetic field (Fig. 1) into the opposite hemisphere. He concluded that about 600 electrons/cc were required to account for his results.

In Storey's theory groups or trains of whistlers of uniform spacing are the result of repeated reflections of the whistler at the two ends of the path. Since the delay of a whistler at a given frequency, measured quantitatively by the dispersion, depends on the length of the path, each successive hop should show a delay which is an integral multiple of the first hop delay. With source and observer in opposite hemispheres, the first whistler would have traveled once over the path, the second three times, the third five times, etc. The ratios of dispersions, or time delays, in this case would then be 1:3:5: . . . Conversely, if the source were in the observer's hemisphere, a loud click would be heard followed by a train of whistlers in which the dispersion ratios would be 2:4:6: . . . Storey confirmed experimentally that (1) whistlers preceded by clicks (which he called long whistlers) were dispersed about twice as much as those which were not (called short whistlers); and that (2) the dispersion ratios of echo trains preceded by strong clicks were even integers, while for the others the ratios were odd.

Since all of Storey's whistler observations were made at a single location, he was unable to check his prediction that whistlers should be confined to an area of about 1000 km radius. The first test of this point was made between Stanford, California, and Seattle, Washington, a distance of 1140 kilometers [*Crary, Helliwell,* and *Chase,* 1956]. The times of occurrence of whistlers at the two locations were recorded two hours each week for one year, and the results showed that about 25 pct of the observed whistlers were coincident at the two stations. This result was interpreted to mean that the whistler energy was localized within an area of dimensions comparable with the station spacing, in good agreement with Storey's theory. The next test of Storey's theory was made between Stanford and the USS *Atka* during her trip to the Antarctic in December 1954. Loud 'tweeks' recorded on the *Atka* while she was near Stanford's conjugate point correlated in time with short whistlers recorded at Stanford. With aid of WWV time signals recorded on both tapes it was found that the Stanford whistlers were delayed with respect to the correlated *Atka* tweeks by about one second, as required by Storey's theory [*Crary* and *Helliwell,* 1956]. It was discovered that the causative sferic was readily detectable on the Stanford record. In September 1955, correlated whistler trains were recorded at Unalaska and its geomagnetic conjugate at Dunedin, New Zealand, by *Morgan* and *Allcock* [1956]. Their results, further confirming the theory, showed several whistler trains with the 1:3:5: . . . dispersion ratios at one end of the path and 2:4:6: . . . ratios at the other end together with the preceding sferic. The predicted nonoccurrence of whistlers near the geomagnetic equator was confirmed by *Koster* and *Storey* [1955] in a three-year study at Achimoto, in what is now the nation of Ghana in West Africa. These tests, although adding nothing substantially new to the picture of whistler propagation, nevertheless provided much needed confirmation of Storey's remarkable theory of the path of propagation.

Recent New Discoveries

Nose whistlers—After the main features of Storey's theory were checked, attention was directed toward a more detailed study of the theory and the experimental data. The first new fact to be uncovered was the existence of whistler components above the previously assumed upper limit of ten kilocycles. Recordings made at Stanford with wideband equipment revealed that whistler components occasionally could be detected up to 30 kc, or more. Spectrum analysis of such high frequency whistlers showed a small but definite discrepancy between the frequency-time curve and the Eckersley dispersion theory. These together with similar discrepancies observed by Storey prompted a study of the Eckersley law which had been obtained by assuming

that the whistler frequency was always small compared with the electronic gyrofrequency.

When this restriction was removed a different equation was obtained which predicted a most surprising characteristic [*Helliwell* and others, 1956]. Assuming sufficiently large plasma frequency, the group velocity is approximately

$$v_g = 2cf^{1/2}(f_H - f)^{3/2}/f_H f_0 \qquad (2)$$

which reduces to (1) when f_H is large compared with f. It shows that when the whistler frequency becomes one-quarter of the gyrofrequency the group velocity reaches a maximum (corresponding to minimum time delay) and decreases for either increasing or decreasing frequencies. The new theory thus predicted a double whistler with simultaneous falling and rising components. Experimental confirmation was obtained at approximately the same time from records made by J. H. Pope of the Geophysical Institute, College, Alaska (geomagnetic latitude 65°) [*Helliwell* and others, 1956]. A spectrogram of one such record is shown in Figure 2a. It is a plot of amplitude, measured by the relative darkness of the display, as a function of frequency and time. (The origin of the time axis is arbitrary since the causative sferic, believed to have originated in the southern hemisphere, could not be identified.) It clearly shows several roughly parabolic-shaped traces, with rising and falling parts extending about 1500 cycles on either side of the starting frequency. Because of the characteristic shape of the individual whistler trace, this particular kind of whistler has been called a 'nose whistler' and its starting frequency the 'nose frequency.' (In this theory, ordinary whistlers are simply the lower branches of nose whistlers.) It can be seen that the several nose whistlers form a train in which the nose frequency decreases with time. These particular whistlers recorded by Pope were the first evidence of whistlers at high latitudes, and it was difficult to know whether they were in fact a confirmation of the new dispersion theory or whether they might be a special type of whistler characteristic of high latitudes.

The theory predicted that the nose frequency would occur at ever increasing frequencies as the latitude was reduced, since the gyrofrequency increases as the latitude is reduced. To test this point, wideband recordings were made at Seattle, Washington (geomagnetic latitude 54°), from which nose whistlers of the predicted type were obtained. A spectrogram of one of these is shown in Figure 2b, with the direct signal from the causative discharge appearing at $t = 0$. This whistler consists of three main parts, the first of which looks very much like other medium

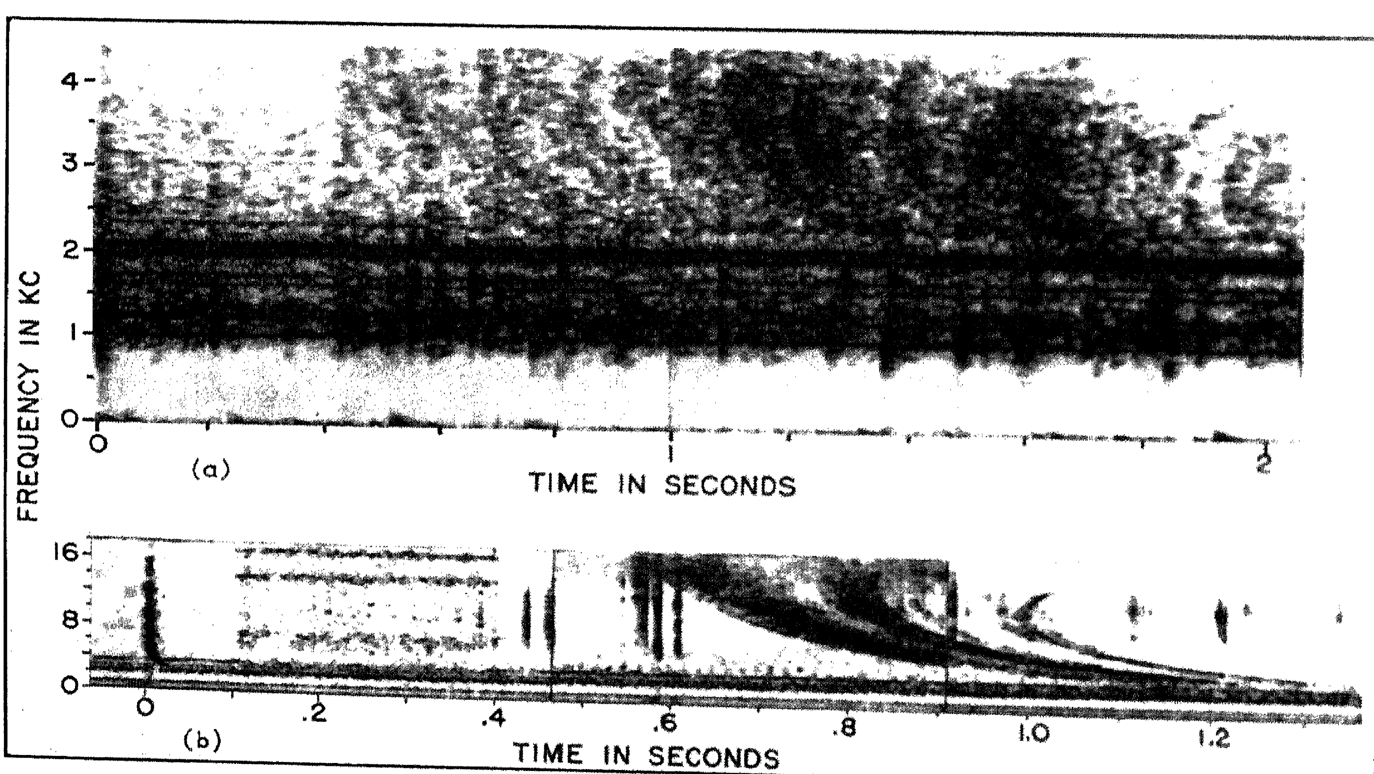

FIG. 2 — Nose whistler spectrograms; (a) College, Alaska, nighttime, July 10, 1955; (b) Seattle, Washington, nighttime, April 4, 1956

latitude whistlers. However, the next two clearly show noses at 0.83 sec and 1.0 sec. The magnitudes of the corresponding nose frequencies (14.2 kc and 12 kc, respectively) and their decrease with time are in accordance with the prediction of the new dispersion theory. Following the announcement of the theory in December 1955, nose whistlers were identified in records taken earlier by *Dinger* [1956] in Washington, D.C. Recently, trains of nose whistlers were obtained at Boulder, Colorado, by R. M. Gallet and J. M. Watts and are similar in shape to the Seattle nose whistlers shown in Figure 2b.

The discovery of the nose whistler is an important windfall for the IGY whistler program. The reason lies in the effect of the gyrofrequency on the characteristics of whistler propagation. For the relatively low values of gyrofrequency encountered near the tops of whistler paths, the gyrofrequency effect tends to become separated from the effect of electron density. As a result the shape of the nose whistler contains information on the magnitude of the gyrofrequency (and hence the Earth's magnetic field) as well as information on the distribution of ionization. With this added information it is theoretically possible to place limits on the location of the path of propagation and, in addition, to obtain the distribution of ionization along the path. With 'classical' whistlers it would be possible only to determine the integrated value of the ionization over an assumed path of propagation.

A further extension of the dispersion theory has been made by *Storey* [1956] for the purpose of using whistlers to detect the presence of ionized hydrogen in the outer atmosphere. He has shown that because the gyrofrequency of hydrogen ions (about 600 cycles in the ionosphere) is comparable with whistler frequencies, there should be a small departure of the dispersion curve from that with electrons only. He points out that the effect should be readily detectable at about 45° magnetic latitude and at frequencies below about two kilocycles. Such measurements require low-noise locations and a maximum of precision in the recording techniques, but should yield information of extremely great value relative to the concentration of hydrogen in the exosphere.

Whistler paths—Although the Stanford-Seattle coincidence tests demonstrated that a given whistler could be heard over an area at least 1000 km across, there was no detailed information on the differences in the recordings at spaced stations. The first definite evidence of significant differences was obtained from simultaneous recordings of the same whistler train at Stanford, California, and Boulder, Colorado [*Stanford University*, 1956]. The spectrograms are shown in Figure 3. (Spectrograms courtesy of J. M. Watts, of the NBS Boulder Laboratory.) The top pair was made at normal tape speed and covers the frequency range 0–8 kc, although information below about 2 kc was cut-off by hum filters. Each recording shows the causative sferic, believed to have originated in the southern hemisphere, followed by the whistler and four echoes. The dispersion ratios are clearly 1:3:5:7, characteristic of a 'short' whistler. At the lower left are the 0–16 kc spectrograms of the first whistler of each train, made by playing the tapes at half speed. This is a clear indication of the fine structure differences between two stations. The Stanford record shows two main components, characteristic of the so-called whistler pair, while the Boulder record shows no such pairing and exhibits a greater range of time delays. (On the Stanford record, the two additional traces with greater time delays are harmonics of the strongest whistler component, resulting from equipment overloading. Harmonics and cross-modulation products appear in several places on the spectrograms where the whistler components are very strong.) The cause of the whistler pair and the differences in fine structure is not definitely known; it has been suggested that the separate whistler components result from the concentration of energy along particular paths of different lengths [*Stanford University*, 1956]. Such concentration might be caused by irregularities in the ionosphere or field-aligned columns of ionization in the exosphere. The radiation pattern of the source will likewise modify the amplitude distribution. The synchronized space-station recordings during the IGY should provide a sound basis for studying such fine structure effects. Their understanding may well be one of the important clues to the mechanism of formation and dissipation of ionization in the exosphere.

Recent work by *Maeda* and *Kimura* [1956] shows that the whistler path may depart markedly from the magnetic field-line path, particularly at low latitudes. However, there is yet no

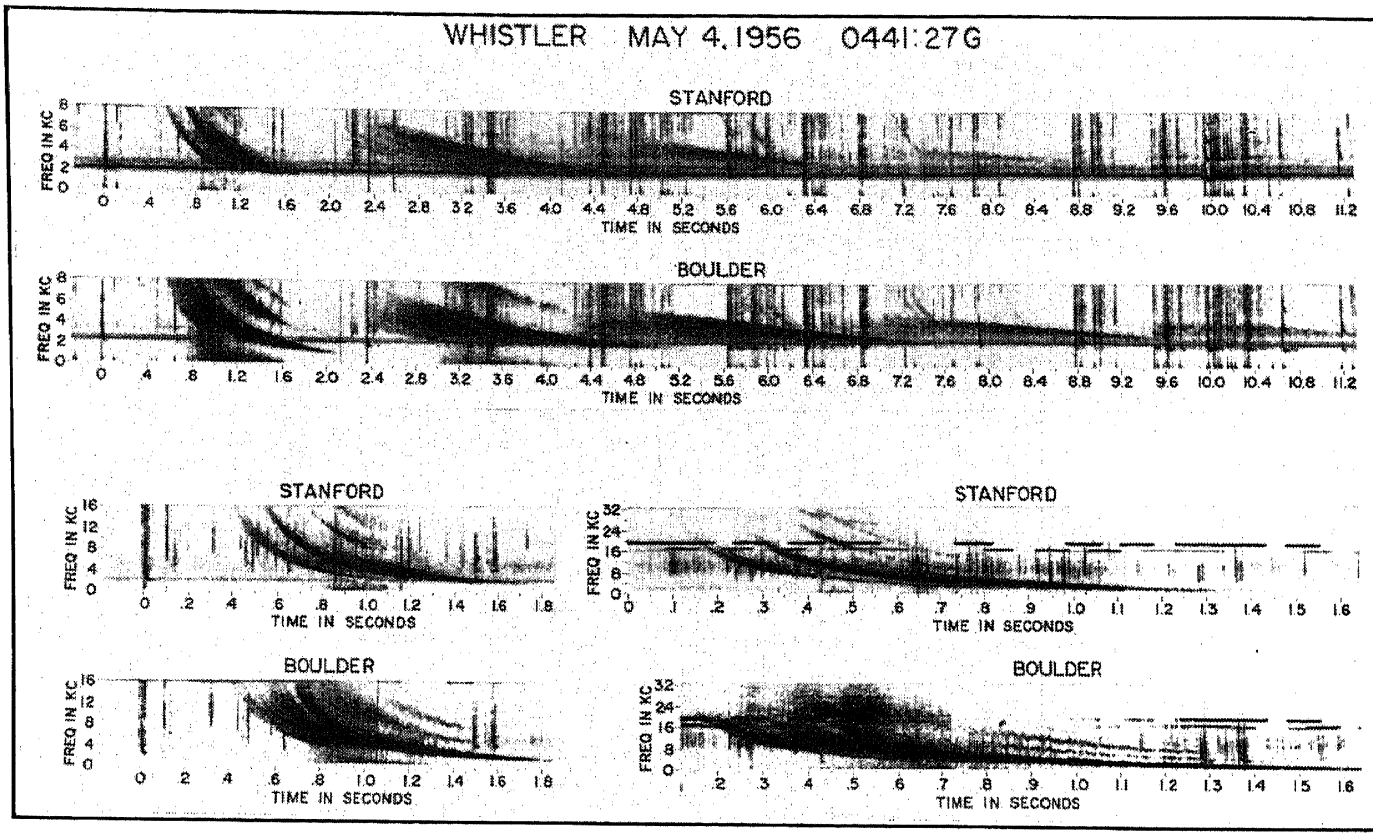

FIG. 3 — Stanford-Boulder simultaneous whistler spectrograms, May 4, 1956, 04h 41m 27s GMT

experimental confirmation of their calculations. Careful measurement of the locations of both ends of the path appears to be necessary.

Very little is known about the effect of the location of the source on the properties of the whistler. If each whistler component travels along certain preferred flux-line paths, as suggested above, then only their relative intensities, and not their dispersions, would depend on the discharge location. Clearly, the locations of the causative discharges are required in the study of whistler paths.

Energy spectrum—The energy spectrum of the source is required if the energy spectrum of the whistler is to be interpreted in terms of the properties of the transmission medium. A new technique for measuring the location and the waveform of the impulse preceding whistlers was successfully tested in September 1956 [*Helliwell, Taylor,* and *Jean,* 1958]. Waveform recording techniques developed by the NBS Boulder Laboratories and broadband direction finding techniques developed at Stanford were applied for the first time in a two-station study of the sferics which precede whistlers. From this test, three new results were obtained. First, the lightning discharges causing the whistlers observed in this test were unusual in that their peak energy appeared at frequencies near five kilocycles, while most of the other sferics observed showed peaks much closer to ten kilocycles. Second, whistler-producing lightning discharges tended to occur more frequently over sea than over land. Third, the time of origin derived from the Eckersley-law interpretation of the whistler was up to 0.4 sec after the observed time. Such a large discrepancy increases the difficulty of identifying the causative sferic from time measurements. It has been explained in terms of the breakdown of the Eckersley law [*Smith* and *Helliwell,* 1957]. In most cases, the waveforms of the whistler-producing sferics were so unusual that it was possible to predict the occurrence of the whistler in several cases by observation of the sferic waveform only. However, this does not mean that the more typical sferic cannot produce a whistler, only that it is less likely to do so because its energy content in the whistler band is lower.

Controlled experiments—The most recent development of significance to the IGY whistler program is the successful completion of an experiment to detect a whistler-mode signal from a man-made source [*Helliwell* and *Gehrels,*

1958]. Special pulse signals transmitted from the Navy station NSS at Annapolis on 15.5 kc were received near Cape Horn, South America, where there is no detectable man-made noise. The regular ionosphere-reflected or 'direct' signals from Annapolis were received strongly at all times. Signals traveling over the whistler path, or what has been called the magneto-ionic duct, were 10 to 30 decibels weaker than the direct signals. The assumed path is shown by the dashed line on Figure 1. The measured time delays averaged about 0.7 sec, in close agreement with delays measured from whistlers recorded at the same time. The corresponding electron density for a constant density model is about 5000 per cc., a value many times higher than that found by Storey.

Double echoes were sometimes observed indicating definitely that more than one path exists in the outer ionsphere. A surprising new result was obtained from measurements of the amplitude which, during some periods, varied in a fairly regular way, over a ratio of ten to one. The fading period was somewhat less than one minute and indicated a systematic variation in the properties of the medium of propagation. Such data may yield new insight into the short-period fluctuations of ionization in the exosphere.

Vlf emissions—Although there are many unanswered questions concerning whistler propagation, it is far better understood than the other types of naturally occurring audio frequency signals generally described as vlf emissions. A typical spectrogram is illustrated in Figure 4, and shows hiss, which is the dark band from about 2 kc to 4 kc, and chorus, which is the series of short rising bands extending from about 4 to 7 kc. Some of these phenomena appear to be related to whistlers and they all show a high correlation with magnetic disturbance [*Watts,* 1957]. They are most prevalent at high latitudes, but a recent study indicates that they do not extend to the geomagnetic pole [*Curtis* and *Morgan,* 1956].

Recently a theory has been advanced to account for these unusual electromagnetic signals [*Gallet* and *Helliwell,* 1957]. It is based on selective traveling-wave amplification of noise energy present in the medium. Energy for the amplification process is provided by streams of ionized particles which come from the Sun and travel along the lines of the Earth's magnetic field. These streams are assumed to penetrate the ambient ionization of the exosphere with relatively little interaction. The mechanism of amplification is assumed to be similar to that in ordinary traveling wave tubes except that the slow wave circuit (provided by the helix of the tube) is the ambient ionization of the exosphere in the presence of the Earth's magnetic field. In such a dispersive medium the velocity of an electromagnetic wave is reduced and becomes of the same order of magnitude as the velocity (order of one-tenth the velocity of light) of the streams coming from the Sun. This is the necessary condition for the transfer of energy from the incoming stream to the electromagnetic wave.

Certain quasi-steady signals, such as hiss and constant tones, are thought to result from a relatively steady stream of solar particles. The

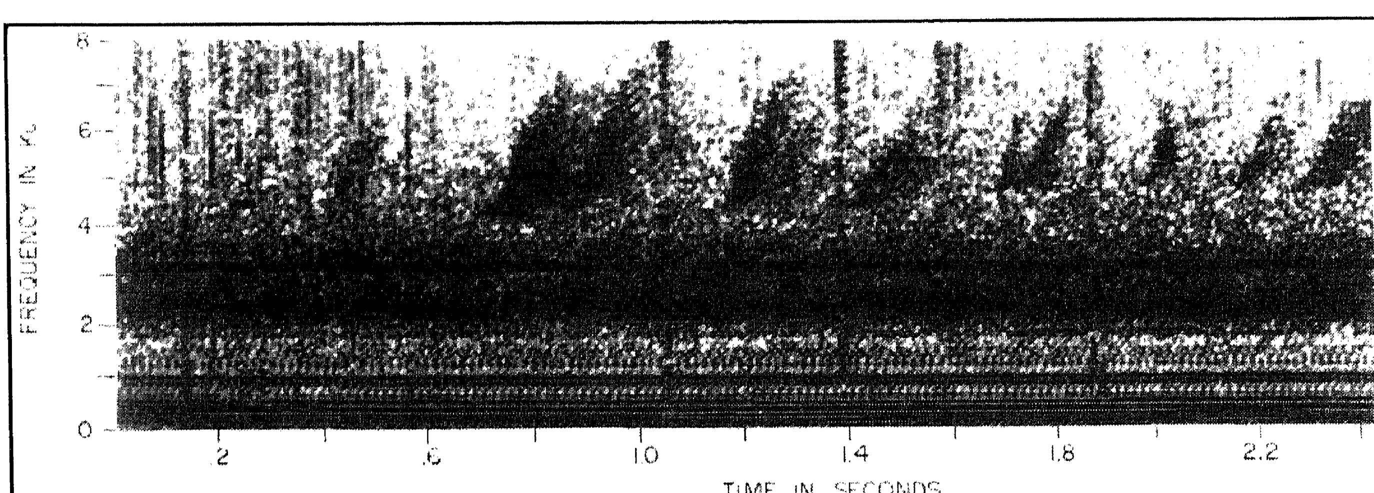

FIG. 4 — Spectrogram of hiss and dawn chorus recorded at Boulder, Colorado, May 15, 1956, 12 h 35 m U.T. (courtesy of R. M. Gallet and J. M. Watts)

transient signals, such as the dawn chorus shown in Figure 4, are more difficult to explain. It is postulated [*Gallet* and *Helliwell*, 1957] that the same amplification mechanism applies, but that the ionized stream is broken up into bunches which excite each frequency for a relatively short time.

Using this theory, *R. M. Gallet* and *A. Hessing* [1957] have calculated the shape of the vlf emissions to be expected from a bunch of charge passing through the region just above the F2 layer. These shapes are remarkably similar to certain hook-shaped emissions observed during periods of magnetic disturbance.

An important part of the IGY whistler program is the study of vlf emissions for the purpose of testing the traveling wave theory or developing new theories of their origin. The phenomena may provide a new way to measure the densities and velocities of solar streams.

Program Requirements

Broadly speaking, the main objective of the IGY whistler program is to determine the occurrence and characteristics of whistlers and vlf emissions at regular intervals and at many locations on the Earth's surface. However, recent new discoveries have led to certain revisions in the specific requirements which were envisioned in the early planning stages. At many of the stations the upper limit of the frequency range has been increased from 10 kc to 30 kc in order to obtain essential nose whistler data. Storey's proposed hydrogen-ion experiment has emphasized the need for high-quality data at the low frequencies, the present lower limit being set at 400 cycles. Its effect is further to stiffen the requirements for low-noise sites. The correlation of spaced-station data on whistlers, and particularly vlf emissions, requires high timing accuracy. Time standards accurate to better than 0.1 sec are needed and represent one of the main items of equipment expense.

The location and size of the effective area for both whistlers and vlf emissions are needed for locating the end points of the paths and measuring the amount of focusing produced by the Earth's magnetic field. For this purpose small groups of stations are set up with a minimum station spacing of about 500 km. Latitude effects are studied with a chain running all the way from the geomagnetic equator to the pole. To determine local-time effects on the distribution of ionization of vlf emissions in the exosphere, several stations well spaced in longitude are also included.

There is good reason to believe that the paths of whistlers may depart appreciably from the lines of the Earth's field [*Maeda* and *Kimura*, 1956]. Furthermore the exact form of the Earth's field at large distances from the Earth is not known. Groups of conjugate-pair stations have been arranged to provide data on the locations of the end-points of whistlers which execute two or more hops. Equally important in the study of the position of the path is the location of the causative lightning discharge. It is measured with vlf direction-finders at a limited number of stations.

The energy spectrum of whistlers may contain valuable data on losses and focusing effects along the path. However, the whistler spectrum is of little use unless the source spectrum is also known. The source spectrum is obtained from recordings of the waveform of the causative sferic.

With these requirements in mind an integrated network of 27 stations was established, 23 of which are operated by United States, three by Canadians, and one by Danish scientists. They are listed in Table 1 according to coordinating institution. The stations at Stanford and Boulder also make DF and waveform measurements using new wide-band techniques. DF data for the whistlers-east group are made available by the Air Weather Service of the U. S. Air Force.

Instrumentation

Automatic whistler recorder—Although whistlers can be detected with the most elementary equipment (for example, a long-wire or loop antenna, a phonograph amplifier, and a set of earphones), the requirements which have been described can be met only with specially designed wide-band equipment. The basic prototype for the antenna and low-noise pre-amplifier developed by L. H. Rorden [*Stanford University*, 1956] has been adapted to the IGY requirements. A simplified block diagram of the Stanford automatic whistler recorder is shown in Figure 5. A one-turn loop antenna is mounted in a vertical plane supported by a single pole or tower. The loop is connected to a balanced low-impedance pre-amplifier which is supplied with direct cur-

TABLE 1 — *Locations of IGY whistler stations*

U. S. whistlers-east (Dartmouth College)	U. S. whistlers-west (Stanford University)	Canada (Defence Research Bd.)	Denmark (Mr. Ungstrup)
Thule, Greenland	College, Alaska	Saskatoon, Sask.	Godhavn, West Greenland
Frobisher Bay, NWT	Kotzebue, Alaska	Ottawa, Ontario	
Knob Lake, Quebec	Anchorage Alaska	Halifax, Nova Scotia	
Father Point, Quebec	Unalaska, Alaska		
Hanover, N. H.	Seattle, Washington		
Battle Creek, Mich.	Boulder, Colorado [a]		
Washington, D. C.	Stanford, Calif.[a]		
Bermuda Is.	Wellington, N. Z.[b]		
Gainesville, Fla.	Dunedin, N. Z.[b]		
Cape Horn, Argentina	MacQuarie Is.[c]		
Port Lockroy, Antarctica [d]			
Ellsworth Station, Antarctica			

[a] Sferics DF and waveform recorder in addition to whistlers.
[b] By cooperation of New Zealand.
[c] By cooperation of Australia.
[d] By cooperation of the United Kingdom.

rent only and is located at least 250 ft from the recording station to reduce power line interference. At the recording station the output of the pre-amplifier is mixed with two sets of time signals, of 0.1 sec duration, derived from a 100-kc crystal standard. One, at about 500 cycles, is repeated every second and the other at about 300 cycles, every ten seconds. These low frequencies were chosen so as to avoid interference with whistler frequencies. The local standard also controls a master clock which automatically programs the operation. In addition to starting and stopping the tape recorder, the clock switches in WWV for the first nine seconds of recording followed by a short amplitude-calibration signal.

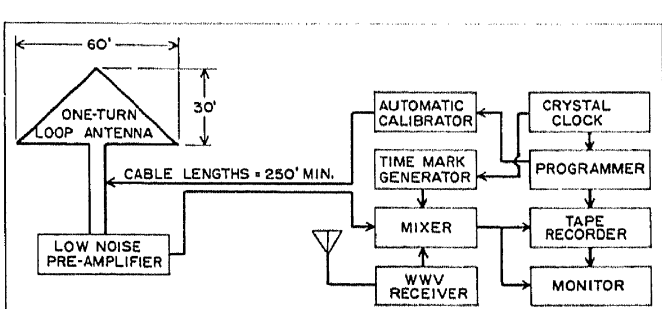

FIG. 5 — Block diagram of Stanford automatic whistler recorder

The time signals from WWV (1000 cycles) overlap those from the local standard and thus provide for its automatic calibration. Voice time announcements from WWV are included as a check on the computed hour of the run.

Direction-finder and waveform recorder—At Stanford and Boulder direction-finding and waveform recorders are installed at each whistler station. Two mutually perpendicular loops are used and their outputs, after passing through the pre-amplifiers, are fed to the x and y amplifiers of the direction-finding oscilloscope. A separate vertical-antenna channel supplies 'sense' signals for the DF and also the waveform which is displayed on a separate oscilloscope. A 35 mm camera photographs both the DF and waveform scopes whenever a sferic is received which exceeds a certain selected amplitude. The time to the nearest second is photographed on each frame. To correlate sferics film recordings with whistler tape recordings, a special pulse is generated at the time the sferics recorder is triggered. This pulse is mixed with the whistler signals from one of the loop channels. When the spectrogram is made, this pulse can be identified and used to determine the exact time of occurrence of the sferic relative to any whistlers on

the tape. In this way, most large impulses which cause whistlers can be identified and their directions and waveforms obtained.

Spectrum analysis—All data are recorded on magnetic tape, which will be stored for later analysis. Presently available methods for the spectrum analysis of these signals are relatively slow, requiring more than five minutes for each two seconds of signals. It is hoped that more rapid equipment can be obtained before it is necessary to analyze large amounts of tape. An analyzing system typical of those in use at the present time has the following features. The 'Sonagraph,' a spectrum analyser, repeatedly scans a 2.4-sec section of signal recorded on a rotating magnetic drum. A marking stylus is geared to a bandpass filter which slowly changes frequency as the drum rotates. With each rotation of the drum the amplitude is plotted, in terms of the relative darkness of the record, as a function of time. During rotation, the filter frequency changes slowly so that at the end of one rotation the frequency has been increased and the stylus moved slightly upward on the paper. The final record is then a plot of amplitude versus frequency and time. The spectrograms of Figures 2, 3, and 4 were made with such an instrument.

The study of spectrograms made from the IGY whistler recordings should answer many questions raised by earlier experimental and theoretical work, and provide the first comprehensive view of the exosphere of the Earth. Furthermore, it is reasonable to expect that the program will lead to further discoveries in this comparatively new field of investigation.

References

Barkhausen, H., Zwei mit Hilfe der neuen Verstärker entdeckte Erscheinungen, *Phys. Zs.*, 20, 401–403, 1919.

Burton, E. T., and E. M. Boardman, Audio-frequency atmospherics, *Proc. IRE*, 21, 1476, 1933.

Crary, J. H., R. A. Helliwell, and R. F. Chase, Stanford-Seattle whistler observations, *J. Geophys. Res.*, 61, 35–44, 1956.

Crary, J. H., and R. A. Helliwell, *Experiments on whistlers and associated atmospherics,* URSI Paper, Spring Meeting, Washington, D. C., May 1956.

Curtis, H. W., and M. G. Morgan, *Whistler and dawn chorus occurrence above the auroral zone,* URSI Meeting, Berkeley, California, October 11, 1956.

Dinger, H. E., Whistling atmospherics, *Nav. Res. Lab. Rep. 4825,* Sep. 14, 1956.

Eckersley, T. L., Letter to the editor, *Nature,* 122, 768, 1928.

Eckersley, T. L., Developments in the study of wave propagation, *Marconi Rev.,* July-Aug., 1931.

Eckersley, T. L., Musical atmospherics, *Nature,* 135, 104, 1935.

Gallet, R. M., and R. A. Helliwell, A theory of the production of VLF noise (so-called dawn chorus) by traveling-wave amplification in the exosphere in the Earth, *Symposium on the propagation of VLF radio waves,* pap. 20, Boulder, Colorado, January 23-25, 1957.

Gallet, R. M., and A. Hessing, *Numerical computations from the theory of VLF noise emissions and their comparison with observations,* Commission 3, URSI Meeting, Washington, D. C., May, 1957.

Helliwell, R. A., J. H. Crary, J. H. Pope, and R. L. Smith, The 'nose' whistler, a new high latitude phenomenon, *J. Geophys. Res.,* 61, 139–142, 1956.

Helliwell, R. A., W. L. Taylor, and A. G. Jean, (letter to the editor, accepted for publication), *Proc. IRE,* 1958.

Helliwell, R. A., and E. Gehrels, Observations of magneto-ionic duct propagation using man-made signals of very low frequency, *Proc. IRE,* 46, 785–787, 1958.

Koster, J. R., and L. R. O. Storey, An attempt to observe whistling atmospherics near the magnetic equator, *Nature,* 175, 367, 1955.

Maeda, K., and I. Kimura, I, A theoretical investigation on the propagation path of the whistling atmospherics, *Rep. Ionosphere Res. Japan,* 10, no. 3, 105–123, 1956.

Morgan, M. G., and G. McK. Allcock, Observations of whistling atmospherics at geomagnetically conjugate points, *Nature,* 177, 29–31, 1956.

Smith, R. L., and R. A. Helliwell, Calculation of the electron density of the outer ionosphere using whistlers, *Symposium on the propagation of VLF radio waves,* pap. 22, Boulder, Colorado, January 23-25, 1957.

Stanford University, Low-frequency propagation studies, pt 1, whistlers and related phenomenon, final rep., Contract AF 19 (604)–795, June 15, 1953, to September 30, 1956.

Storey, L. R. O., PhD. dissertation, Cambridge University, England, and *Phil. Trans. R. Soc. A.,* 246, 113–141, 1953.

Storey, L. R. O., A method to detect the presence of ionized hydrogen in the outer atmosphere, *Can. J. of Phys.,* 34, 1153–1163, 1956.

Watts, J. M., An observation of audio-frequency electromagnetic noise during a period of solar disturbance, *J. Geophys. Res.,* 62, 199–206, 1957.

Radio Propagation Laboratory, Stanford University, Stanford, California

Probing the Ionosphere

A. H. Shapley and Ralph J. Slutz

Introduction—While the existence of ionized layers in the atmosphere was postulated in 1902 by Kennelly and Heaviside to explain the possibility of transatlantic radio communication as demonstrated by Marconi in 1901, it was not directly observed by experimentation until 1925. Then Appleton and Barnett reported tests using a frequency modulation technique which distinctly showed the existence of a reflecting layer, and in 1926 Breit and Tuve independently reported similar results from the reflection of radio pulses. These experiments showed that the ionosphere consisted of not just one but several reflecting layers, and that their characteristics changed markedly with time, both regularly throughout each day and irregularly when sudden disturbances or ionospheric storms take place.

The experimental techniques used in these studies went on to become the forebear of modern radar. The data recorded concerning the ionosphere were found during the 1930's to be of marked value in the planning and operating of long-distance communications. This practical application to communications resulted in much more attention to radio sounding of the ionosphere than would have been the case had it been a pure geophysical experiment. With the pressure from communication needs, the use of radio sounding has been continuously and actively developed. Many successively improved models of sounding equipment have been designed, and during 1955 there were some 90 stations throughout the world recording ionospheric sounding data on a regular basis.

As more and more is observed about the ionosphere it has been found to be more and more complex. Having its origin largely in solar radiations, its characteristics vary extensively throughout the day, throughout the year, throughout the eleven-year solar cycle, and with latitude and longitude on the Earth's surface. Previous to the IGY, the major emphasis has been on detailed study of the time variations of the maximum electron density over individual stations. The IGY program includes the possibility for improved studies of this kind but because of the vastly increased number of observing stations and the careful selection of locations for newly installed stations, the possibility arises for shifting the emphasis to regional or global studies of the ionosphere.

In this paper we are examining some of the very early results from parts of the IGY network of vertical sounding stations and the potentialities for other phases of this large-scale experiment.

Diurnal variation of F2 in polar regions—One of the questions asked very early in the planning stages for the IGY was whether and in what way the F2 layer ionization is maintained during the polar night when for several months there would be no ion production by means of direct solar radiation. The north-polar flights with an airborne ionospheric sounder by Gassman [1956] in 1954 and 1955 showed that there was a very appreciable electron density still remaining in the F2 layer during the long winter night. However, these observations were necessarily too fragmentary to give evidence about the source of this ionization or how it was maintained. Very preliminary reports of ionospheric soundings taken at the newly-established South Pole station confirm the existence of a dense F2 layer near the time of the winter solstice and gave evidence of major fluctuations in rather short periods of time. It is interesting that the mean values of foF2 for the South Pole (Fig. 1) show a very probably significant diurnal vari-

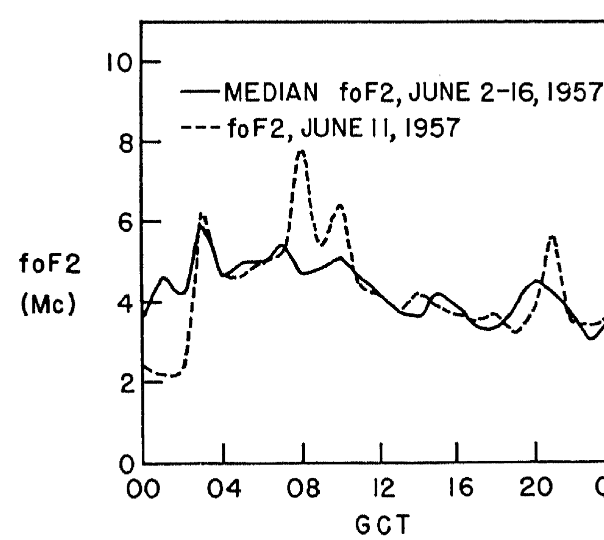

Fig. 1 — Vertical incidence ionospheric sounding from the South Pole station

ation, even though the solar zenith angle is constant (and greater than 90°) throughout the 24-hour period. The maximum of foF2 occurs at about 7h UT. Since this is approximately noon of geomagnetic time, it seems probable that the mechanisms which produce this average diurnal variation are under geomagnetic control. It should be emphasized that the fluctuations within a day are often of greater magnitude than the mean diurnal variation shown. Another feature of the South Pole reports thus far received has been the large percentage of the time when the F region echoes were so diffuse that no measurement of critical frequency could be made. This feature, which is consistent with Gassman's brief observations on his North Pole flights, may seriously bias the results shown in Figure 1.

North-south polar ionospheric relationships—Until the installation of IGY stations, there was very little information on the equivalence of ionospheric characteristics in the two polar regions. This is a subject which will require detailed study of original ionograms which are not yet available. A clue, however, comes from the data fragments received from the U. S. Wilkes Station (Fig. 2) where it appears that the F2 electron densities during the brief winter day compare well with equivalent northern hemisphere measurements. The comparison during the night hours seems so far to be poorer.

Geomagnetic effects—Ionospheric soundings made in polar regions can also give us some information on the three-dimensional form of

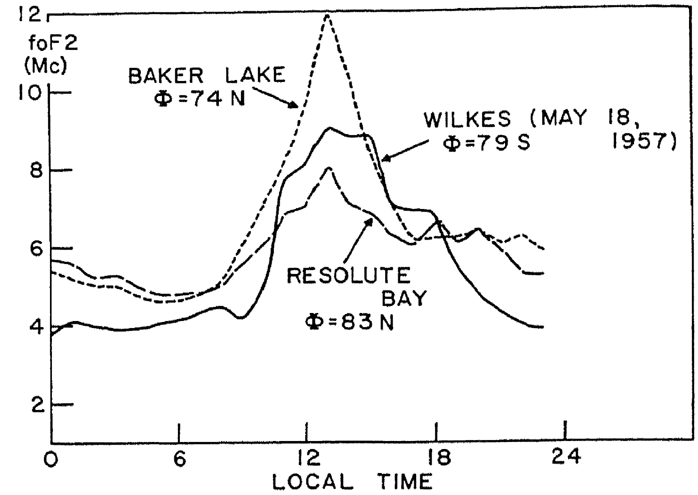

FIG. 2 — Comparison of ionospheric soundings from North Polar and South Polar regions

the Earth's magnetic field. According to the simple picture of the Earth's field, the field should tend to be vertical at great heights at the geomagnetic poles. The new IGY station at Thule, less than 2° from the north geomagnetic pole, has obtained many soundings which are typical of these magnetic conditions. Figure 3 shows the appearance of the Z component in the echo traces from all layers, which is often observed under these magnetic conditions, in addition to the ordinary and extraordinary components. With a number of higher-powered equipments, such as the Thule C4 ionosonde in use during the IGY, considerably more observations of this type can be expected.

North-south auroral relationships—Another question being asked of the IGY observations is whether short-lived auroral phenomena, or their

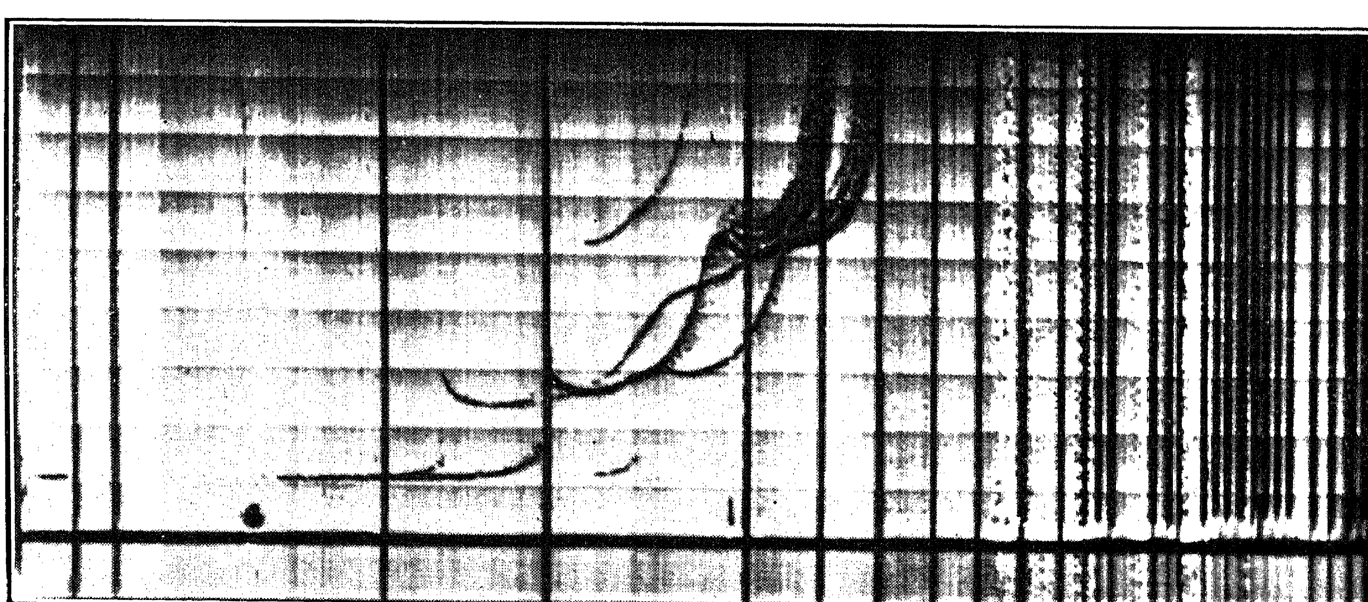

FIG. 3 — Thule ionogram for April 27, 1957, 15 h 27 m local time, showing complete O, X, and Z traces

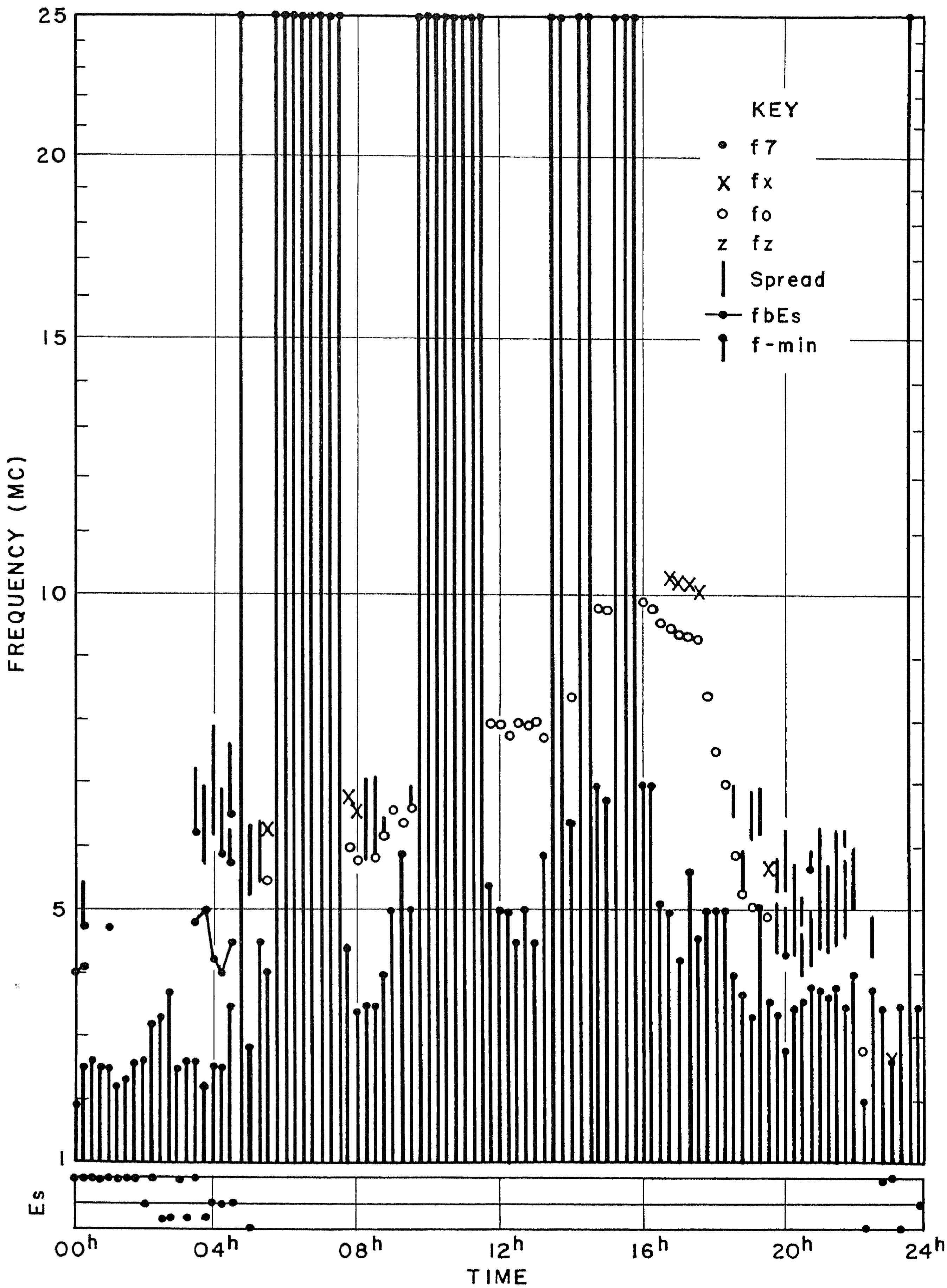

FIG. 4—Plot of ionospheric critical frequencies showing three brief periods of high absorption

ionospheric and geomagnetic counterparts, occur simultaneously in the northern and southern hemispheres. Assuming that these phenomena are produced by streams of solar particles impinging on the Earth, simultaneity in the two hemispheres would indicate that the stream was of roughly uniform density in cross section and that it was not polarized. If phenomena do not occur simultaneously, then it should be concluded the details of auroral and geomagnetic phenomena in the auroral zones were more strongly influenced by terrestrial conditions. It will be difficult to carry out this experiment with the aurora itself, because there are very few common hours of darkness in the two auroral zones. The experiment, however, can be made in a less precise fashion using the ionospheric sounding observations since the typical ionospheric effect of a discrete auroral outburst is increased absorption of radio waves. Figure 4 shows an f-plot for Fairbanks, Alaska, upon which appears three different short intervals of very high absorption. These phenomena do not occur very often and can be used as a first approach to answering the question of simultaneity. Reports are already being received from the South Pole station on phenomena of this sort but out of the first six cases no clear instances of simultaneity with instances on the North Polar cap have been found.

Network studies—In the IGY network of vertical sounding stations, deliberate emphasis has been placed on installing any new stations at locations which will give a concentration of stations from pole to pole along selected meridians. This is perhaps the nearest one can come to making a planned worldwide experiment with ionospheric vertical soundings, for it will allow the delineation of latitude profiles, while minimizing the number of factors influencing the ionospheric electron densities and specifically aid in the untangling of the coupled effect of solar and geomagnetic control. An example of this kind of experiment is shown in Figure 5, showing an empirically-derived latitude variation curve of foF2 using median observations from pre-IGY stations along the meridian passing through the Americas. The details, even the whole form of the empirical

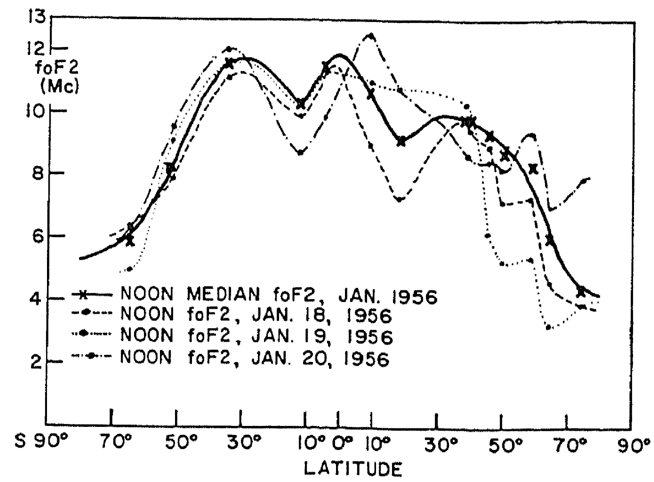

FIG. 5 — Latitude variation of observed noon foF2 along 75° W chain of ionosphere stations

curve, are open to some question. This is further emphasized when the observations for individual days are examined and the dissimilarities from one day to the next match. It is hopeless to try to solve this question with the pre-IGY distribution of stations but now that the gaps are being filled this is a question which can be studied in detail. The detailed mechanism of geomagnetic control of F region electron densities and the amount and nature of horizontal transport of ionization should emerge from these IGY observations.

These are examples of the ways in which probings of the ionosphere by vertical soundings can help form a picture of the ionosphere on a global scale and settle many uncertainties about the interaction of the Earth's magnetic field with ionospheric regions. Such problems will be also aided by more precise experiments at fewer locations which will be undertaken during the IGY, and are described in the United States program. The vertical soundings network, about ten stations in 1939 and now 165 stations during IGY, provides the foundation for our concepts of the global ionosphere and its variations and for these more specialized studies.

REFERENCE

GASSMAN, GEORGE J., Airborne ionospheric measurements in the North Pole area, *J. Geophys. Res.*, **61**, 136, 1956.

Central Radio Propagation Laboratory, National Bureau of Standards, Boulder, Colorado

Upper Atmospheric Winds, Absorption, and Other Special Projects in the U. S. Program in Ionospheric Physics

H. W. Wells

Introduction—The International Geophysical Year is a sequel to the Second International Polar Year of 1932–33. In fact, the present term 'Geophysical Year' was adopted after favorable world-wide reaction made it apparent that the use of 'Polar Year' would be too restrictive a description of the international program. Results of the research activities in the Polar Year of 1932–33 stimulated further exploration of the upper atmosphere and provided a groundwork for important discoveries which have greatly advanced knowledge of the Earth's outer atmosphere and of the Sun. The initial impetus which was given to stations such as the Huancayo Observatory (Peru) and the Geophysical Institute, College (Alaska) has aided their development into important facilities in the present IGY program. The period following the International Polar Year of 1932–33 was one of gradual but vast changes in basic concepts of many areas of geophysics. As technological developments led to greatly improved instruments for research, many isolated or strange results began to form a distinctive pattern. For example, our concept of the outer atmosphere, or ionosphere, gradually evolved from that of a static shell of ionized gas surrounding the Earth to a dynamic envelope—sensitive link between Earth and Sun—with clouds, winds, tides, storms, and other disturbances.

In the IGY program, there are several special projects in areas of ionospheric physics which are designed to fill in gaps in our knowledge of unusual properties of our outer atmosphere. A simple recital of these special projects —absorption, winds, true heights, etc.—would not stimulate much enthusiasm. However, the following paragraphs will describe the scientific interests and objectives. In building this technical foundation, it is necessary to draw on the prior work of many scientists without adequate personal recognition. Their collective results form a degree of 'status quo' from which the IGY program takes over in order to extend our frontiers of scientific knowledge. These special projects are like seeds which are being watered by the IGY program. Most of them will sprout, grow, and bear fruit. Some will mature or ripen within a year, while others will develop more slowly. Both the national and international scientific harvest will be greatly stimulated by the concentrated effort of many research workers over the world.

Our atmosphere has been referred to as a sensitive link between Earth and Sun. It is also a protective blanket and screen which filters out harmful ultraviolet radiation and protects us from bombardment by particles or waves from outer space. We now know that our normal outer atmosphere contains several banks or layers of electrons and ions at heights from 60 to 200 or more miles above the Earth. This region is known as the ionosphere. The electrified particles are produced by the impact of solar radiation on the gases in our rarified atmosphere. When the Sun is disturbed, as by sunspots or related activity, its radiation can be greatly increased for periods lasting for several minutes to hours. One effect of a solar eruption is the production of another bank of ions, this time at a level substantially lower than normal. We realize that the undisturbed ionosphere supports, and in fact makes possible, long-distance high-frequency communications (Fig. 1). But the solar-disturbance type of layer causes partial to complete absorption of the high-frequency signals with interruption to communications. You may ask, why does one layer of ions cause reflections while the other causes absorption? A partial answer rests in the fact that the solar-disturbance ion bank is produced at substantially lower heights than normal. At these lower heights, the energy in the radio waves is dissipated because electrons, which are set in motion by the radio waves, collide with gas particles which are much more numerous at the lower height. The result is absorption of the exploring radio waves (Fig. 2). The above remarks are admittedly over-simplified, but the principle is sound.

In addition to waves, the disturbed Sun may also emit particles which are subsequently at-

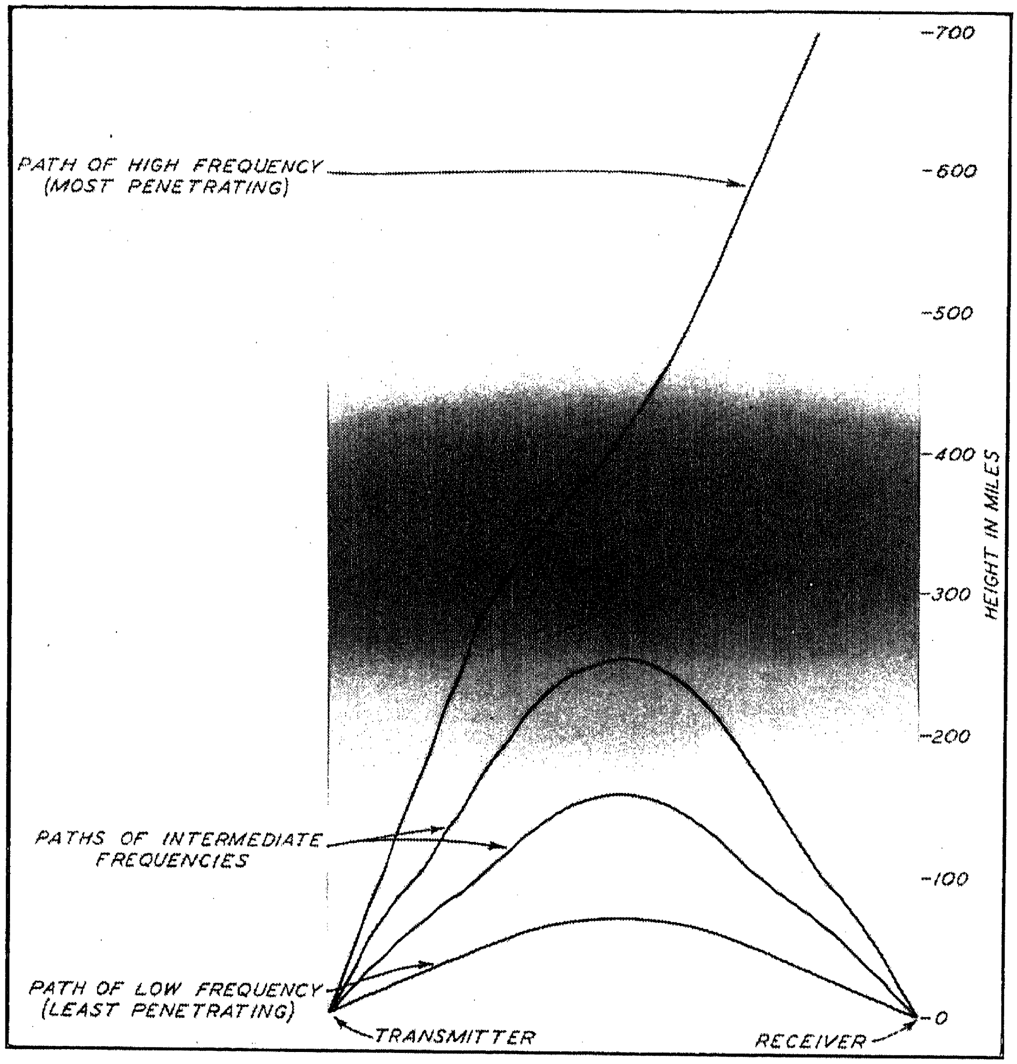

Fig. 1 — Paths of radio waves of different frequencies in the ionosphere, normal conditions

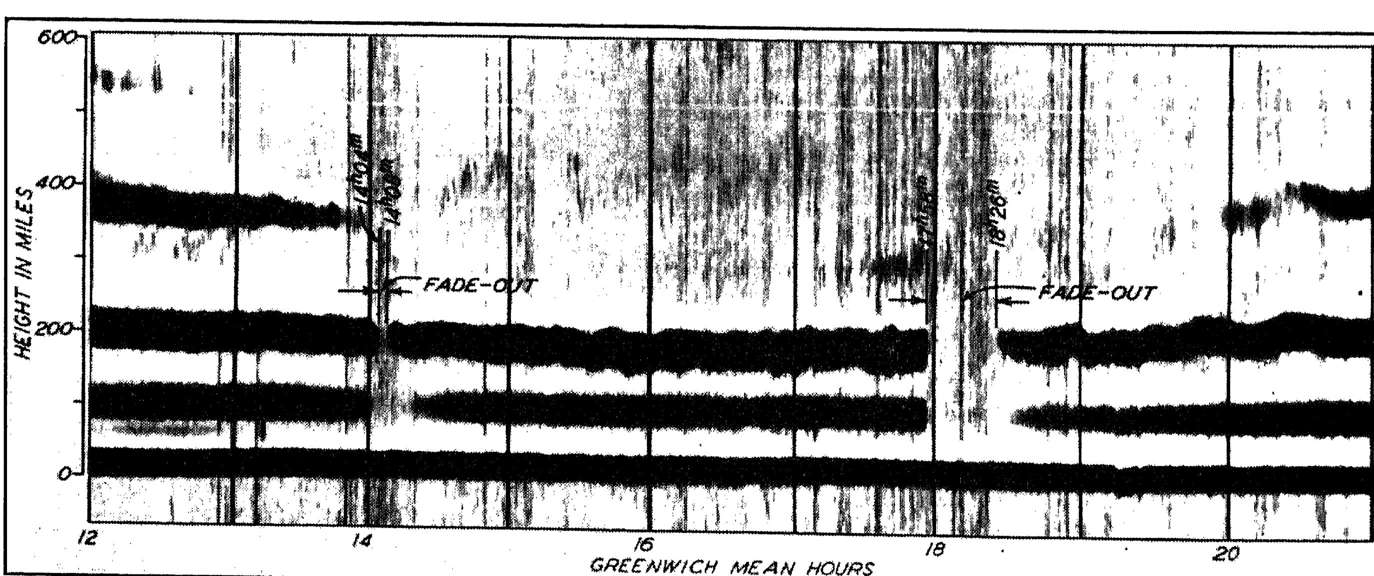

Fig. 2 — Radio fadeouts resulting from solar flares (the radio signals are absorbed in temporary layers of ionization produced by the solar flare)

tracted into polar regions by the magnetic field of the Earth. The particles travel much slower than light and require about a day in transit between the Sun and Earth. One result of such particle bombardment is the well-known aurora. Associated with aurora is another form of absorption which makes normal high-frequency radio communications subject to frequent interruptions. In addition to the absorption produced by such particle bombardment, clouds of intense sporadic ionization (above the absorbing level) have been linked with the aurora-type bombardments. We find, therefore, that radio-wave absorption in our outer atmosphere is a sensitive finger on the pulse of solar activity. Knowledge of the absorption and its vagaries establishes a valuable aid to radio communications. It obviously stimulates studies of solar-terrestrial relationships and usefully extends knowledge of the Earth's upper atmosphere and magnetic field.

Measurements

Absorption—During the IGY, programs for absorption measurements are being conducted at the Geophysical Institute, University of Alaska, and at Pennsylvania State University. The ionospheric-absorption apparatus operated by the University of Alaska utilizes a principle which has recently been developed, known as the 'cosmic-noise method.' They measure the 'relative ionospheric opacity' and name their instrument a *rio*meter. It measures the intensity of radio noise from outer space, cosmic noise (Fig. 3). The cosmic radio signals, which resemble a very weak hiss, reach the receiving antenna after penetrating through the entire atmosphere of the Earth. The normal level or intensity of cosmic noise is quite stable and unchanging. However, any temporary increase in absorption by our atmosphere produces a decrease in the received signal level. A recent report states, "Tests have shown that the equipment is capable of continuous measurements of the relative ionospheric opacity to a high degree of accuracy provided interference-free channels exist."

The 13 instruments being acquired are to be installed at sites in Alaska, Canada, United States, Greenland, and Sweden. Their prototype riometer is being operated in a routine

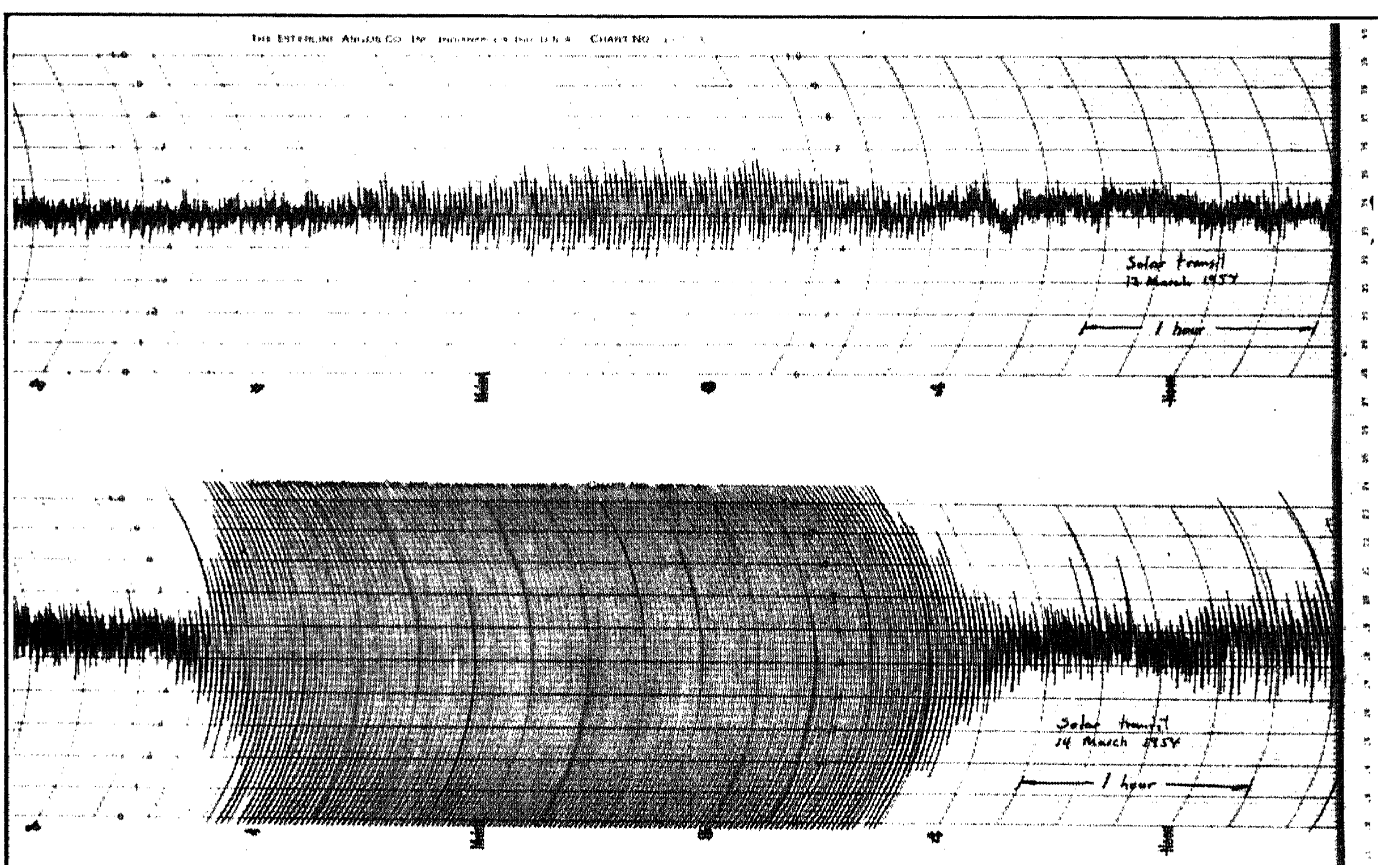

Fig. 3 — Radio noise from quiet Sun and disturbed Sun (a disturbed Sun also showers the Earth with noise-like radio signals)

manner near the University of Alaska. Initial reports are very satisfactory and several periods of strong absorption have already been observed.

At Pennsylvania State University, the program for measurement of absorption uses a different principle which may be considered somewhat more conventional. A short radio pulse is transmitted vertically and the intensity of the reflected signal or echo is recorded. Observations during normal or undisturbed days establish a basis of reference and any significant reduction in echo intensity may be used as a measure of absorption over the path of the exploring radio waves. We find that Canada plans to operate a chain of five absorption measuring stations of this type which, along with the stations at Pennsylvania State University, will extend measurements from temperate to arctic regions. Preliminary measurements are already underway, well in advance of the IGY.

Winds and drifts in the upper atmosphere—Now let us examine another special project; namely, that of winds and drifts in the upper atmosphere. At first glance, our specific effort in this area appears to be rather meager, but an examination of composite programs in several IGY disciplines shows that much information on this subject will evolve as a by-product from other programs. Although the term winds has been somewhat loosely applied to drifts or other movements in the upper atmosphere, one must not be misled to assume that winds in the conventional sense are always implied. It is difficult to think of winds blowing in a vacuum. Although a comprehensive discussion of upper-atmospheric movements is beyond the scope of this report, it may be useful to make brief mention of the present state of knowledge of this subject. The meteor-Doppler methods used in the United States, England, and Australia show drift velocities between 100 and 200 mi/hr. There are large semidiurnal components, and the drift direction rotates clockwise, with time, in the northern hemisphere but counterclockwise in the southern hemisphere. Heights are, of course, limited to meteor levels roughly corresponding to the E-layer of the ionosphere at 60 to 70 mi.

Radio-fading methods for E-layer winds give velocities in the same range, 100–200 mi/hr, show a strong semidiurnal component, and clockwise rotation in the northern hemisphere.

Radio-star scintillations appear to establish that similar clouds or patches of electrons are being swept through the upper atmosphere at velocities of from 200 to 800 mi/hr. The scintillations are predominantly a nighttime effect. The cloud dimensions are irregular but average from one to six miles. These drifts seem to take place at heights approximately 300 mi above the Earth, but there is not uniform agreement concerning this altitude. During magnetic and auroral disturbances, the scintillation rate is much faster, suggesting a corresponding increase in drift velocity (Fig. 4).

Measurements of winds by scintillation methods require the use of a network of ground stations, preferably three, which are spaced not more than a few miles apart. The radio-star scintillation observed at one station will show a similarity to that of an adjacent station but with a small time-displacement which is used to calculate a component of velocity and direction. The combination of observations over different baselines establishes the apparent velocity and direction of movement of the cloud producing the scintillation. Admittedly, there are some complicating factors which enter into the analyses, since the shape of the irregularity must be taken into consideration. However, the basic principle is as described above. Upper-atmospheric winds are being observed by this method at the University of Virginia and at the University of Puerto Rico.

The installation at the University of Puerto Rico is a liaison activity, being sponsored by the Geophysics Research Directorate, Air Force Cambridge Research Center, which reports that substantial progress has been made and that a successful observing program is anticipated during the IGY. We have also been advised that the University of Puerto Rico is planning another type of wind measurement, based on a fading technique which requires the use of one transmitting station and a triangulation of receiving stations. These observations will give data of ionospheric movements at heights which can be rather well specified. Hence, the simultaneous operation of instruments probing two different levels in the upper atmosphere should be especially valuable.

Propagation under unusual conditions—In another special activity sponsored by the IGY, the Air Force Cambridge Research Center has enlisted the cooperation of over 1000 amateur radio operators in Japan, Central America, and South America, in addition to many in the United

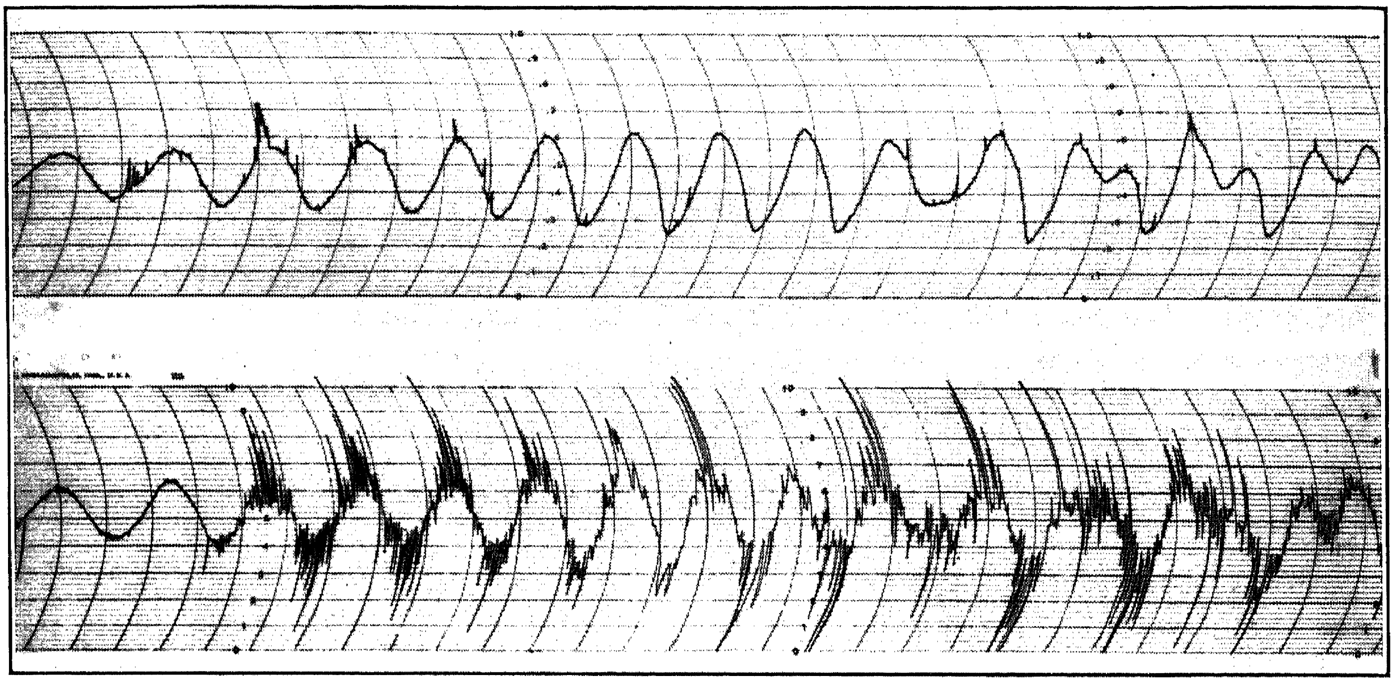

FIG. 4 — Signals from radio stars, quiet and scintillating (the rough appearance of the lower record is due to twinkling or scintillation of the radio star caused by winds or drifts about 300 mi above the Earth)

States. The whole-hearted cooperation of the American Radio Relay League is responsible for the great progress and organization which has been completed. The participating radio amateurs are encouraged to report all strange or unusual signals or periods of communication. There are many effects, especially at this period of high solar activity, which create temporary but extremely unusual communication conditions. For example, amateurs communicating on a band which is normally useful for line-of-site ranges may suddenly find themselves establishing two-way communications over vast distances. At times, their signals may be bounced off of auroral curtains, at other times clouds of sporadic-E ionization will provide the reflecting medium, or perhaps the scatter of signals from meteor showers may be the mechanism of propagation. Other strange communication conditions, such as the occasional contacts between amateurs in the northern and southern hemispheres over distances of 4000 or 5000 mi, are still relatively unexplained, in view of the fact that the frequency band in use is normally limited to short-range operations. The central headquarters for this propagation project will sift and partially analyze all of the incoming reports so that the information may be utilized later to develop our understanding of many strange events which occur in the upper atmosphere.

True height computations—Another special project has perhaps less observational glamour but is a fundamental requirement for both theoretical and practical progress in a complete understanding of the Earth's outer atmosphere. I refer to the work at Pennsylvania State University for the determination of true heights. All of the methods of radio exploration of the outer atmosphere provide apparent or virtual heights. The exploring radio wave is often substantially delayed in its progress through the ionized regions. Hence, the heights which are determined from a method of measuring time-delay between pulse and echo are often very much greater than the actual or true height of the reflecting region. An adequate description of the methods would be too involved for this report. However, one should note that the normally tedious calculations are to be greatly expedited in the Pennsylvania State University program through the use of specially developed electronic computers. The results of this activity are bound to have a long continuing influence on both theoretical research and practical applications involving our outer atmosphere.

CONCLUSIONS

The preceding remarks describe some special IGY activities in the field of ionospheric physics in very broad and general terms. It is impossible,

of course, to do justice to the human element involved. In these as well as other IGY research programs, there are many hours of planning, many hours of burning the midnight oil, before the real opportunity of marking the specific measurements gets under way. Often these are accomplished under adverse and difficult conditions. The overall progress will result from an integration or summation of all the contributions made by the thousands of individuals who are sweating away at specific activities. The combined outcome will undoubtedly include a few important but isolated discoveries. However, the really sound and basic advances to be achieved in the IGY are bound to be the result of concentrated efforts and a pooling of data by scientists in this country and in other nations of the world. Without reservation, I feel we can look forward to the IGY as a period of rich enhancement of scientific knowledge leading to better relations with our neighbors in other countries of the world.

Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.

Background and Technical Objectives in Geomagnetism

Elliott B. Roberts and David G. Knapp

Introduction—Magnetism, and its specialized form we call terrestrial magnetism, or geomagnetism, were among the earlier mysteries of nature. Ancient man, fascinated by the properties of lodestones and by their affinity for iron objects, speculated endlessly but never found good answers to his questions. His perplexities were compounded in later times with the discovery that magnetized objects, when floated on water or suspended freely by a thread, sought to align themselves closely with the meridian (Fig. 1). In the writings of an oriental scholar of the eleventh century, we find the following:

> "A geomancer rubs the point of a needle with the lodestone to make it point to the south, but it will always deviate a little to the east. . . . To use the needle, it may be put on water . . . on the nail of a finger, or at the lip of a bowl, but . . . the best method is to hang it up by a thread where there is no wind. . . . And no one could as yet find the principle of it."

Modern man, though he knows much of the effects of magnetic fields and though he has literally revolutionized his life by their use, still does not know what magnetism is, except that we know that it is one facet of the broad category of electromagnetic effects. It may be said that a magnetic field is but a manifestation of an electric field in motion; but this is merely another description, not an explanation.

In the IGY, we will continue man's long search for more knowledge of this force. We do not seek the basic physical theory of magnetism which has eluded man's systematic scrutiny through the ages. We intend in fact to deal with only a small part of one special magnetic field, that of the Earth; and not to ask what it is, but why it changes as it does.

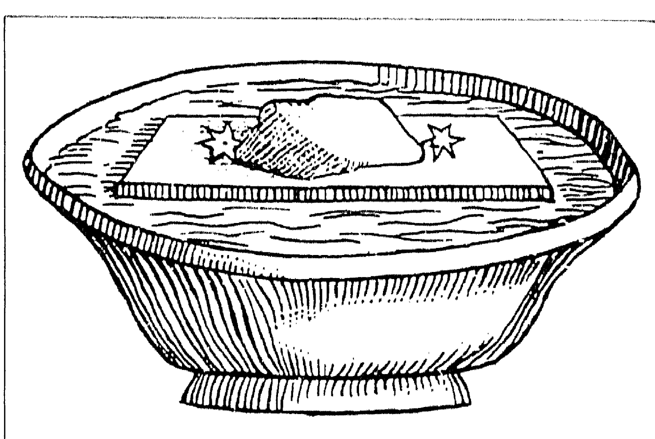

Fig. 1 — Medieval floating compass as shown by Athanasius Kircher, *Magnes sive de arte magnetica,* 1643

Geomagnetism is a complex phenomenon. By far its greater part is relatively stable, consisting of fields generated within the Earth, complex in form, and with only a slow secular change whose cause still rests in the realm of speculation. Perhaps five per cent of the field observed at the Earth's surface consists of highly variable components associated with electrical current streams in the atmosphere. It is this transient part of the field that we will seek out for study. The search is part of a whole body of investigations in related fields including ionospheric physics, aurora and airglow, radio-wave propagation, cosmic-ray patterns, terrestrial effects of solar activity, and meteorology.

New techniques have been developed. Stations have been laid out in arrays more dense than ever before. Some sixty-six nations are joined in the search. We expect to learn much of the nature and causes of geomagnetic time fluctuations.

History

The isolated passage quoted above has often been taken to mean that the Chinese knew of magnetic declination before its discovery in Europe. This, however, is scarcely warranted, since the same author seems to say that if perfectly performed the experiment would disclose the true south. It appears that a real knowledge of declination arose during the first half of the fifteenth century in western Europe. As a matter of fact, Columbus is frequently credited with the discovery of magnetic declination, more particularly of the fact that it differs from place to place. Although this is debatable, he was among the earliest navigators to visit regions of large compass declination and he speculated much on his difficulties in the reading of the compass.

The story of magnetic investigations is to a great extent tied to that of Arctic expeditions. It is now 400 years since Stephen Borough's voy-

age to Kara Strait brought back the first knowledge of magnetic declination in high latitudes. Many other explorers have added to this store in the course of the long history of Arctic exploration, but their findings were for the most part devoted to mapping the permanent field, until the discovery of transient fluctuation around the end of the seventeenth century.

The mapping of the permanent field is the theme of a long and arduous chronicle, punctuated by stories of heroism and sacrifice that only a Homer could adequately portray; but that story is not of direct concern to the IGY effort. It remained for the discovery of the daily variation of declination in 1685 to disclose for the first time one of the aspects of geomagnetic phenomena which have become the subject of our present efforts. In that year, a party of French missionaries, guests of the King of Siam, recorded a succession of declination observations which failed to agree, the reported results of seven observations showing a spread from 16′W to 38′W. All the observations were made at the same place in Lop-Buri, Thailand, hence they may be regarded as the first disclosure of what we now call transient fluctuations, though the Jesuit scientists may not have been aware of the significance of this.

Credit for the actual identification of this fluctuation belongs to a London clockmaker and amateur philosopher named Graham. In 1722, after many hundreds of observations, Graham made a definite announcement of his discovery. His findings were verified and amplified by the Swedish astronomer Anders Celsius, using a special needle. Other investigators followed. Celsius and his colleague and successor Hiorter of Uppsala, Sweden, discovered the existence of sporadic and chaotic types of magnetic activity (Fig. 2). The seasonal change in the daily variation of declination was brought to light by Canton in 1759, and its inversion in southern latitudes by John MacDonald in 1795.

Whereas the Swedish observers had noticed the striking coincidence of magnetic perturbations with the aurora, observers in lower latitudes, who saw the aurora less frequently, maintained a healthy skepticism toward what must have seemed a fantastic notion, a connection between apparently unrelated phenomena. The English astronomer Edmund Halley had suggested a theoretical connection on other grounds; nevertheless, the point remained in dispute for a century until the association was finally established beyond question by George Back during his exploration of the Canadian Arctic in the 1830's, and by Lottin and Bravais at Bossekop in the North Cape area of Norway in 1838–1840. This, of course, was after the existence of a physical relation of magnetism and electricity had been clearly established in the laboratory. Meanwhile, Sabine had made the first protracted series of high-latitude magnetic observations in 1819-1820, at Winter Harbour on the coast of Melville Island. In 1819 the Swedish astronomer Hansteen published the first comprehensive treatise on all the then-known phenomena of geomagnetism.

While Poisson and Airy, and later Archibald Smith, were delving into the mathematical basis of compass deviation and the magnetism of ships, there was a great upsurge of experimentation and discovery in the newly opening field of electromagnetism. Basic laws began to emerge in rapid succession. It became clear that the Earth's magnetic field afforded a convenient working medium on which to base the measurements of electric current, but the measurement of the magnetic field itself was in an unsatisfactory state, because all intensity readings were directly dependent on the strength of magnetization of the needles used, a shifting and uncertain factor. This handicap was brilliantly dispelled by the work of Karl Friedrich Gauss of Göttingen. He developed, along the lines of suggestions by Poisson, a method of measuring both the horizontal intensity of the Earth's field and the magnetic moment of the magnet, by a coordinated experiment involving oscillations and deflections with a single instrument. In most every respect the Gaussian technique was far superior to the older methods, and it placed intensity measurement on a uniform basis such that henceforth the determinations of different observers, made apart, could be directly compared and coordinated.

Gauss was one of the first to perceive the importance of making continuous observations of daily variation and other transient phenomena of the Earth's magnetism, particularly in regard to a host of minor features that had not been discernible in the earlier, grosser measurements. He shares with Weber, Humboldt, and Sabine the credit for promoting the establishment of magnetic observatories at widely separated points.

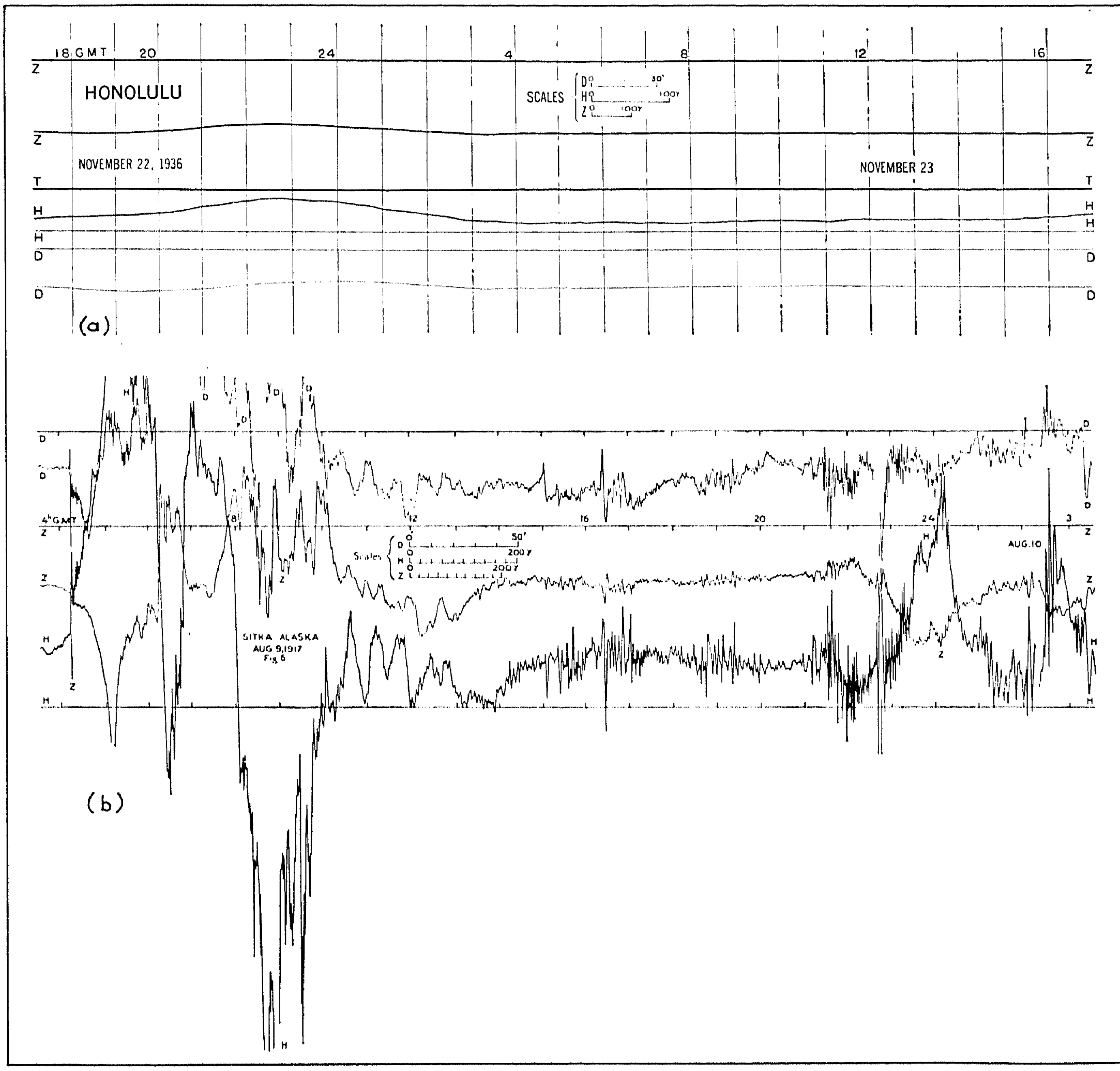

Fig. 2 — Contrasting magnetic variation records, portrayed by (a) a typical quiet day recorded at Honolulu, and (b) a day of magnetic storm recorded at Sitka; straight lines on magnetograms are base lines for use in scaling values

Gauss and Weber established a magnetic observatory in 1832 at Göttingen, to this day a great center of geomagnetic investigation, and to make their investigations meaningful they developed suitable instruments for observing the variations of declination and horizontal intensity. It is interesting to compare the bifilar variometer of that day, having a magnet more than three feet long that weighed 25 lb, on a suspension 17 ft long, with a modern instrument having a magnet no longer than a carpet tack, suspended on a filament of quartz less than six inches long.

Magnetic observatories were established at widely separated points to secure simultaneous data regarding the variations of the Earth's magnetism. Some of them were soon discontinued, but others continued in operation much longer, some (as the one at Toronto, Canada) even to the present day. Thanks to the zeal of Alexander Dallas Bache, later superintendent of the Coast Survey, a magnetic observatory was operated at Girard College, Philadelphia, from 1840 to 1845, and some variation observations were made in Washington from 1840 to 1842. One of the meteorological and magnetic

observatories established by Russia, at Sitka, Alaska, was in operation from 1842 to 1867. In spite of the cumbersome instruments then available, the operation of these observatories served to establish the principal features of the short-period variations of the Earth's magnetism.

Arctic work took on an increasingly prominent role as the baffling complexities of the magnetic-storm effects came to light during the work of various expeditions collaborating in the 20-year search for the lost Franklin expedition. In 1872-1874, newly designed instruments were used in the Franz Josef Archipelago on an arduous program of eye-readings that lasted more than three months. It was Karl Weyprecht of this expedition who perceived the need of coordinated, simultaneous work at the whole network of Arctic stations. It was his initiative that led to the International Polar Expedition of 1882–1883, the progenitor of IGY.

In this first Polar Year, photographic recording was out of the question for remote outpost stations. This meant that the data obtained represented a tremendous expenditure of effort to maintain a 24-hr schedule of hourly or even more frequent readings by eye. The effort, however, bore fruit. These data yielded important statistical knowledge of some of the features of polar magnetic perturbations, and they were a great stimulus to further study devoted to the development of similar data for localities other than those of the Polar Year expeditions.

For Greenland alone, we have such material from Nanortalik by C. Holm, from Scoresby Sund by C. H. Ryder, and from Umanak Fjord by H. Stade. Other observers in this category were A. R. Gordon, who occupied a station on Hudson Strait, J. H. Turner, H. M. W. Edmonds, and J. E. McGrath in the Yukon country, von Toll along Siberian Arctic shores, and members of the Russian-Swedish expedition to Svalbard in 1898-1899. Scandinavian geophysicists have taken a leading part in the growth of knowledge about geomagnetic transients, and in 1902-1903 K. Birkeland of Norway was responsible for the operation of a net of four observatories stretching from Iceland to Novaya Zemlya. Birkeland was thus enabled to achieve advances in magnetic-storm theory that still stand as an important part of the subject. At the same time, the Norwegian explorer Roald Amundsen succeeded in operating a magnetic observatory for 23 months on King William Island; this remained for nearly 50 years the nearest approach of such an operation to the North Magnetic Pole.

Antarctic expeditions, too, have contributed importantly to our knowledge of geomagnetic transients, although the geography of the Antarctic continent does not favor more than a fragmentary or piecemeal assault on the important auroral-zone localities. The German South Polar Expedition of 1901–1903 under von Drygalski operated an observatory at Kerguelen Island; others were established by the British Southern Cross Antarctic Expedition of 1898–1900 under C. E. Borchgrevink (Cape Adare), the National Antarctic Expedition of 1901–1904 under R. F. Scott (McMurdo Sound and Cape Adare), the Scottish National Antarctic Expedition of 1903–1905 under W. S. Bruce (South Orkney Islands), the French Antarctic Expedition of 1903–1905 under J. B. Charcot (Palmer Peninsula), the British Antarctic Expedition of 1910–1913 under R. F. Scott (McMurdo Sound and Cape Adare), and the Australasian Antarctic Expedition of 1911–1914 under D. Mawson (Cape Denison). The work at Cape Denison was the basis of an extended study by Charles Chree to examine the relations of southern and northern perturbations, although the lack of concerted data at many stations meant that the study was necessarily confined to statistical aspects.

All these activities led inevitably to the Second International Polar Year 1932–1933, when for the first time there were simultaneous photographic recordings at a widespread net of observatories in high latitudes, chiefly in the Arctic. This achievement remains as the primary basis of our present understanding of magnetic storms.

Since then, geophysical knowledge has been gained apace. The equatorial singularities have become apparent, and the probability of systematic relationships between Arctic and Antarctic manifestations is now urgently in need of more detailed scrutiny. Vast theories of upper-atmosphere physics have been erected and they demand test and observation. Radio astronomy opens new vistas that have vital bearing on the phenomena of the region skirting the Earth's atmosphere, as well as the remotest realms of the observable universe. As we attain to more insight into the probable nature of things, it becomes ever more necessary to observe and study. Geophysics is worldwide, and the joint effort of

66 nations is not too much for our present needs. The logical successor to the First and Second Polar Years is naturally our present IGY.

Technical Aspects of the Problem

The geomagnetic IGY program is directed toward some of the problems of the electric and magnetic phenomena of our atmosphere, and of space beyond, particularly as influenced by solar activity. A comprehensive exposition of the theory of transient fluctuations being not yet possible, a brief outline of some of the simple current concepts may help to explain our IGY interest in these phenomena.

It is known, of course, that intense ultraviolet radiation is involved, and that under such excitation the thin gases of the high atmosphere are ionized in layers or zones comprising the ionosphere. At least one such layer is electrically conductive and may convey currents of great aggregate magnitude, with attendant magnetic fields. Solar activity such as spots, flares, and other events vary the rate of ultraviolet radiation, with dramatic effects on the ionosphere.

There are numerous observable effects, some of which, however, do not occur until many hours after observed solar events. For several reasons it is thought that the Earth is also under bombardment by streams of slower moving corpuscles, presumably protons shot out violently from the Sun. It is difficult, however, to account for the high energy and systematic motions of such particle streams.

The magnetic fields existing at the Sun's surface and in the corona must play an important role in the behavior of such streams, and it has been suggested that configurations of such fields may provide a mechanism for the escape of the gas, which consists chiefly of protons and electrons. One theory has it that some emission is a normal feature of relatively 'quiet' areas of the solar disk, but that certain disturbances of the magnetic field associated with the Sun's corona may intensify the emission in certain directions and suppress it in others.

The density of this material is no doubt reduced as it traverses interplanetary space. It may also be deflected by the magnetic fields of coronal and interplanetary gases. But once it encounters the Earth's magnetic field, there are highly important new effects, though of great complexity. One generalization seems to be that the protons are deflected toward the east and the electrons toward the west. The particles are believed to be banked up in such a way as to form a girdle or belt that may completely surround the Earth. Since the protons and electrons are streaming along this path in opposite directions, the net effect is an electric current, and the fluctuations of this supposed current are observable as changes in the geomagnetic field. This equatorial ring current is probably at a considerable distance from the Earth, say several Earth radii, and should not be confused with the ionospheric currents previously mentioned; specifically not with the equatorial 'electrojet.'

The reality of such an equatorial ring current is another problem. Unlike the ionospheric currents mentioned before, this current is supposed to maintain its direction and strength undiminished in all longitudes, but it undergoes temporal changes of several kinds. Its behavior can be tailored to account for the depression of H during a magnetic storm, the subsequent gradual recovery or post-perturbation effect, and the well-marked simultaneity of a great deal of the fine structure exhibited by low-latitude observatory records during magnetic storms. The only trouble is that a suitable distribution of sheet current in the ionosphere could produce these effects, and no experiment has been carried out to settle the matter. This is one of the reasons for the satellite program and rocket experiments. By reason of the general expansion of observatory facilities, the patterns of the phenomena that the equatorial ring current is supposed to explain will be clarified and mapped out in greater detail then ever before.

The streams of gas from the Sun can penetrate much closer to the Earth in polar regions, by following the lines of force of the Earth's main field. When these particles reach the atmosphere, they produce increased ionization and magnetic changes, and luminous discharges which we know as the aurora. The magnetic effects are known, in their severest form, as magnetic storms. Many of the effects are so highly concentrated along the auroral zones as to merit the designation of auroral electrojets. But our knowledge is scant, because most of the storms that have been observed did not occur at times when there was adequate recording in high latitudes. It seems likely that electric fields generated in such latitudes produce complex worldwide current systems in the ionosphere. These

systems would be responsive to rapid changes in the initiating mechanism.

Daily variation. Daily variation appears to have a more understandable physical basis than other features of geomagnetism. It is primary a daytime feature, greater in certain magnetic latitudes, and generally greater in summer than in winter. For declination, the morning and afternoon changes are in reversed direction in the southern hemisphere. It is generally accepted that the cause of this daytime effect is to be found in the daily atmospheric tides, involving both heating and ionization of the upper atmosphere. The mechanism is in brief a dynamo action based on horizontal motions of conducting gases across the vertical component of the main field. The amplitudes are greatest at the times of maximum sunspot activity, and thus afford a useful index to the fluctuations of solar ultraviolet emission. Harmonic analysis indicates that perhaps 75 pct of the daily variations are directly due to causes outside the solid Earth, presumably these upper-atmosphere electric currents; the other 25 percent are due to induced Earth crustal currents.

Early pioneers of magnetic observatory work, on discovering the hemispheric reversal of daily variation of declination, quite properly reasoned that there should be an equatorial zero line. A search for this line was responsible for the establishment of several equatorial observatories. No such definite line exists, but there is a transitional belt where the effects vary seasonally or otherwise from time to time. Although the real situation is too complex to admit of easy explanation, the search for such an equatorial line was fruitful in other respects.

A similar problem exists with regard to the daily variation of magnetic horizontal intensity. Certain equatorial stations show a far greater amplitude of this curve than do stations in other locations. This seems to be confined to a narrow zone, possibly governed by the magnetic equator. It is as if the overhead current system in the ionosphere shows a pinch effect that is most evident where its equatorial portions cross the noon meridian. Furthermore, there are strong indications that not only normal variations, but also irregular activity, such as solar-flare effects and sudden commencements of magnetic storms, are also enhanced under similar circumstances. This relationship has an important bearing on magnetic-storm theory, and one of the problems of the IGY program is to trace out this equatorial 'electrojet' as it has been called, and to obtain enough data on its behavior for a reasonably confident attack on these intricate collateral effects.

General activity—General activity or 'unrest,' which goes on more or less all the time, has long been classified by various systems of activity indices which have been checked and catalogued for many years from numerous parts of the world. A well-marked 27-day recurrence tendency is evident, and is one of the proofs of a solar origin. This activity derives from a variety of causes including continuous minor disturbance of the ionospheric current streams. It is generally more pronounced in the high magnetic latitudes where agitation of the ionospheric region is greatest. For the IGY, a special system of quarter-hourly activity figures has been established for the very frequent reporting of general activity, particularly from polar-region stations.

Although standard magnetic instruments are unresponsive to activity at the higher frequencies, it is known that magnetic fluctuations are continually evident in many frequencies approaching those of radio. The nature of these audio- and subaudio-frequency fluctuations is little understood, although there is reason to believe they are in part the result of lightning discharges. Only meager information as to their areal distribution is now available. An observational program employing induction-type detection instruments is to be operated with several stations in the United States. The results of this work together with similar observational evidence from other countries may serve to explain much about these presently little-known fluctuations.

Magnetic Storms—Magnetic storms comprise a specialized and highly intensified category of magnetic activity. Although the name is analogous with meteorological storms, there is no established correlation with the weather. Magnetic storms are widespread phenomena, generally worldwide in fact, whereas ordinary weather is predominantly of local or regional character. Magnetic storms are related to solar emanations, probably of both ultraviolet and corpuscular types.

Magnetic-storm intensities increase toward the high magnetic latitudes. As an extreme example, in the storm of April 2, 1944, the total

range of declination at Cheltenham was less than one degree whereas at Sitka, Alaska, it was more than nine degrees. In the tropics, magnetic-storm effects are greatest in horizontal intensity and least in declination.

Magnetic-field changes on the Earth's surface during magnetic storms have three main parts: (a) a part proceeding according to time measured from the commencement of the storm, known as storm-time variation; (b) enhanced diurnal variation of a distinctive pattern known as disturbance-daily variation; and (c) irregular effects especially characteristic of high latitudes.

In the study of areal distribution of storm effects, the times of commencement are important. While this is sometimes difficult to ascertain, there are many occurrences of abrupt character known as sudden commencements. As far as is known, these occur simultaneously or at least within a few seconds throughout the world.

A great deal of study has been given to the characteristics of magnetic storms and certain general trends have become evident. There are important, yet not entirely consistent, relationships between solar conditions, particularly sunspot occurrences, and the occurrences of magnetic storms, ionospheric disturbances, difficulties of radio communication, and auroral displays.

Present knowledge of magnetic storms is weighted unduly by the records obtained during a single storm of the Second International Polar Year of 1932-1933. It is clear that the gross features of a magnetic storm comprise a tumultuous and disordered influx of electrically excited corpuscles flowing earthward along the lines of force, and thereby funneled into two 'collars' which are visibly apparent as the auroral zones. It cannot be stated with assurance whether this emanation represents a sort of leakage from the ring current, or whether it comes by a more direct route from the Sun, or indeed whether it might not consist of atmospheric ions thrown out to great distances by reason of an excess of absorbed solar energy. But in any event, it is becoming increasingly evident that the intricate details of a particular magnetic storm present puzzles far beyond the scope of the generalized patterns of statistically averaged storm systems. Surges of current have been observed which produced virtually opposite pulses in the magnetic field at stations only a few hundred miles apart.

A given magnetic storm may show, in low latitudes, a typical 'sudden commencement,' an abrupt and sustained rise in horizontal intensity, followed by irregular activity. Yet in high latitudes the same storm commencement may be characterized by a long train of pulsations and a sharp increase in their amplitude at the time in question.

There are a number of special forms of magnetic disturbance, of which the first to be given special recognition was the bay. This is a departure from an otherwise undisturbed record in the form of a V or a bay of the sea, from which it gets its name. Most bays have no apparent relation to ionospheric and auroral activity, but a special kind of bay is associated with auroral displays and radio fadeouts. This is the 'crochet' which can usually be related to solar flares observed visually at the same time. It is hence designated as a solar-flare effect, and is believed to result from a strong influx of ultraviolet light emitted by the Sun.

Micropulsations—Micropulsations have long been a major puzzle. These long trains of quasi-sine waves can be found in observatory records almost anywhere with sufficiently fine-grain recording. An interesting discovery that grew out of the Second Polar Year was that at certain times and places there are particularly large micropulsations, which have been given the quaint name 'giant micropulsations.' During the IGY, widespread use of rapid-run magnetographs is expected to yield a great mass of pertinent data on micropulsations and other short-time effects.

The IGY Geomagnetic Program

It has been seen that the majority of the transient change effects are directly related to the electric current streams believed to be characteristic of the ionosphere, perhaps also to more remote ring currents and other discharges associated with particle streams in space. It is also clear that the physical nature and morphology of these streams of electrical current have the utmost significance in the study of all aspects of upper-atmosphere phenomena.

As is the case for other major IGY programs, the geomagnetic program is primarily designed to disclose more information about the currents we have discussed. The difficulty in the past has always been a gross insufficiency of observa-

tions. For the observation of highly transient phenomena, moreover, there are needed not only large numbers of observations, but coordination to provide simultaneous timing. The IGY promises vast improvement in these respects, using regular and temporary observatories of standard type, and semi-automatic recording instruments of nearly equal quality of results (Fig. 3).

In Alaska, magnetic registration is carried out at ten well-distributed points across the northern auroral zone. At every one of these stations, continuous records are made of all the field components necessary for full definition of the field. Five of the installations constitute standard observatories, including those at the extreme locations of Barrow and Sitka. A recording instrument is operated at an Arctic Ocean ice-floe station, in addition to those in interior Alaska. Not only does this provide the fullest array of observation points ever to exist in a region of such singular magnetic importance, but in addition a completely new observational principle is used. This is the differential magnetograph, developed by J. H. Nelson of the Coast and Geodetic Survey, on the suggestion of Sydney Chapman.

The differential magnetograph consists in essence of a central recording instrument at the Survey's College Observatory near Fairbanks, to which are connected, by electrical cable, two outpost instruments about seven miles distant in the magnetic south and west directions. The joint operation of the connected instruments results in a record of the magnetic field differences between the central and outpost instruments. Thus the magnetic field gradient in each of two normal directions is disclosed. This information should provide better clues to the location and perhaps the form of ionospheric currents than ever before available.

An added feature of the instrumental array centered on Fairbanks is a pair of standard magnetic observatories, at points about 80 mi south and east of the central station, constituting a similar tripartite array designed to disclose field gradients over an area greatly larger than that of the differential array. Though not

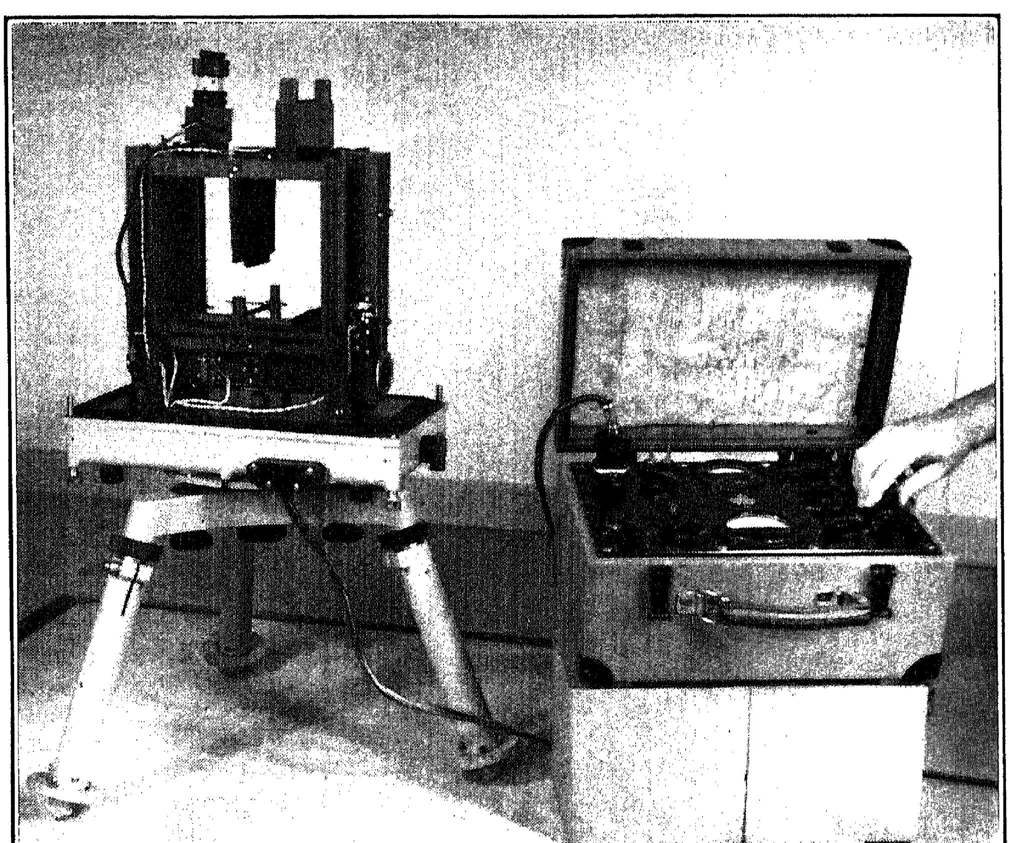

FIG. 3 — Askania variograph, used by many nations at temporary IGY stations; the United States employs 22 of them; compact and portable, this instrument nevertheless produces magnetograms approaching the quality of those from standard observatories

electrically connected, and therefore not arranged to record the differences directly, highly accurate time control is provided, permitting detailed comparison of the records.

Perhaps the next most important undertaking is the intended scrutiny of the equatorial electrojet. For this purpose no less than ten stations are employed in the equatorial Pacific area. A three-station array is to be operated for a period of at least one year, centered on Jarvis Island, 1200 mi south of Honolulu. Jarvis has the distinction of being the only land on Earth at a junction of the magnetic and geographic equators. Two companion stations, at Palmyra and Fanning Islands, outside the presumed path of the electrojet, will function as control or comparison stations. All will consist of the so-called semi-automatic recording instruments.

The United States also operates a standard magnetic observatory on Koror Island in the western Carolines, situated precisely upon the magnetic equator with a companion station of similar character at Guam, some hundreds of miles to the northeast. In Peru, in association with the Huancayo Geophysical Observatory, a north-south chain of five recording stations is operated in an array providing a cross section of the entire electrojet region. The Huancayo Observatory, established many years ago by the Carnegie Institution of Washington for its proximity to the magnetic equator, was the first of several stations providing data that led to the discovery of the equatorial electrojet.

Four stations are operated in Antarctica, of which three are standard observatories. These are distributed in relation to the southern auroral zone so as to provide as much collateral information about overhead currents as possible in that relatively unknown region. A principal contribution of the Antarctic stations will lie in their comparison value with simultaneous records in the North Pole regions. Many theoretical questions will be advanced by fuller information as to the similarity, simultaneity, and general correspondence of observed effects at these two opposite ends of the Earth.

In the west central part of the United States, seven recording stations, arranged in a general east-west pattern, are operated for a distinctly different purpose, that of seeking evidence of correlation between magnetic and meteorological events. Since the progress of weather changes is generally in east-west orientation, such an array of magnetic observation points should provide a wealth of pertinent data for a scrutiny of this elusive question.

At many standard observatories, both regular and temporary, additional equipment for 'rapid-run' recording has been installed, to provide records of great detail. These supplement the work of regular instruments, particularly for the fullest scrutiny and appraisal of the fine characteristics of magnetic storms and other features of the records. Rapid-run instruments built for the United States program represent a distinct advance over earlier types in that they provide a more open record of much finer optical quality, giving full detail and stronger assurance of complete fidelity during the most interesting periods of records.

An important indirect contribution to the maintenance of high performance standards in the IGY program lies in the use of a special array of coils at the Fredricksburg Observatory, permitting adjustment and testing of instruments designed for use in other parts of the world.

In addition to the photographic recording apparatus, there are supplemental recorders at certain key stations, generally where ionospheric records are operated. Thus an immediate ink record, usually of horizontal intensity, will be produced which can be inspected at any time. This will be of help in deciding on special alerts and World Days for intensified programs in case of magnetic storms or other special events.

Implications

Among the major problems that we may hope to attack with the aid of IGY data is that of clarifying the effects of electric currents that develop in the approaching stream of solar matter, as distinguished from these produced in the ionosphere. As for the latter, we can be confident of a better understanding of numerous subordinate features such as the Schmidt vortices that produce certain types of bays and oscillations, and other current patterns that give rise to small, rapid pulsations over limited regions.

From studies of the airglow, it appears that a patchy structure in the ionosphere is subject to drifts which may show up in the records of the east-west chain of magnetic stations in the western United States. Another interesting problem is concerned with the use of sharp

pulses in the geomagnetic record to study the electrical properties of the Earth's crust.

It may well be that new advances will come with the use of hydromagnetic theory in expressing the behavior of matter in the Sun's corona and in the space bordering on the Earth's atmosphere. The role of electric fields in interplanetary space is important in Alfvén's treatment. Singer has stressed another important class of phenomena in this region, namely those associated with shock waves. The relative importance of solar-flare effects in relation to the other transients is another question with many ramifications.

In summary, the United States IGY Program is geomagnetism is expected to develop fundamental information on the electric currents of the high atmosphere, possibly also of the dense lower atmosphere and of outer space.

Division of Geophysics, U. S. Coast and Geodetic Survey, Washington, D. C.

New Experiments Concerning the Geomagnetic Field Extending into Interplanetary Space

J. A. Simpson

Since cosmic-ray particles begin to interact with the terrestrial magnetic field at considerable distances from the Earth, these particles provide important information concerning the description of the magnetic fields extending beyond the surface of the Earth. In earlier publications [*Simpson*, 1956] we have discussed the relationship between magnetic field and cosmic-ray intensity measurements in the equatorial zone and have shown how the high-energy charged cosmic-ray particles act as probes for exploring the shape of the Earth's magnetic field. We defined the line of minimum cosmic-ray intensity around the Earth as the geomagnetic field equator effective for cosmic-ray particles (the cosmic-ray equator). This is an equator extending outward from the Earth into the interplanetary medium.

In 1954 we initiated experiments which were concerned with the following basic questions regarding the terrestrial field. Is the magnetic field which interacts with cosmic-ray particles adequately represented by: (a) the centered or eccentric dipole approximation derived from the spherical harmonic analysis of surface magnetic field data (see, for example, the analysis of Gauss, Chapman, Bartels, and others), or (b) the local measured fields at the surface of the Earth, or (c) for example, partly by a magnetic field distribution extending into the volume around the Earth which arises from the interaction of the rotating permanent field with the ionized medium surrounding the Earth?

The first of these questions was clearly answered by preliminary experiments [*Simpson*, 1956] by showing that the effective equator for cosmic rays was not represented by the classical equator derived from geomagnetic dipole field analysis, and that these differences extended to intermediate latitudes as shown by the longitude effect. In these preliminary experiments we could only justify approximating the experimental points by a sine curve on a Mercator projection, and the answers to questions (b) and (c) remain for further investigation. We have recently undertaken additional experiments which more clearly define the nature of the Earth's magnetic field beyond the surface of the Earth. The analysis of the data is not yet complete but, because of current interest in these questions, we give here some preliminary results of the new measurements. These most recent experiments were performed in collaboration with Peter Meyer of the Enrico Fermi Institute for Nuclear Studies (University of Chicago), and with Ludwig Katz and John F. Butler of the Cambridge Geophysical Research Directorate [*Katz, Meyer, Simpson,* in press].

A nucleonic component monitor composed of two separate neutron detectors and recording circuits was transported by aircraft at constant-pressure altitude (corresponding to 18,000 ft altitude) around the equator according to the route described in Figure 1. The elapsed time for the 12 equatorial crossings was 43 days in 1956, during which time there were only small primary cosmic-ray intensity variations. Corrections for these variations were provided by the neutron monitor data at Huancayo, Peru. Preliminary latitude curves derived from the 12 equatorial crossings are given in Figure 2. From these data both the equatorial longitude effect and the position of the minimum cosmic-ray intensity as a function of longitude may be investigated.

The longitude effect at the equator—The intensity at the minimum of each latitude curve in Figure 2 was measured for 12 longitudes. The deviations from mean intensity around the Earth are shown in Figure 3. This is the longitude effect at the effective geomagnetic equator. The following points are of special interest:

(1) There is a remarkable symmetry in the curve. The maximum and minimum intensities are nearly 180° apart and the areas under the two halves of the curve are approximately equal. There are no large contributions from functions which have a period different from 2π.

(2) The peak-to-peak amplitude is 25 pct. This demonstrates that the equivalent magnetic center of the Earth is eccentric with respect to the axis of rotation. A preliminary calculation

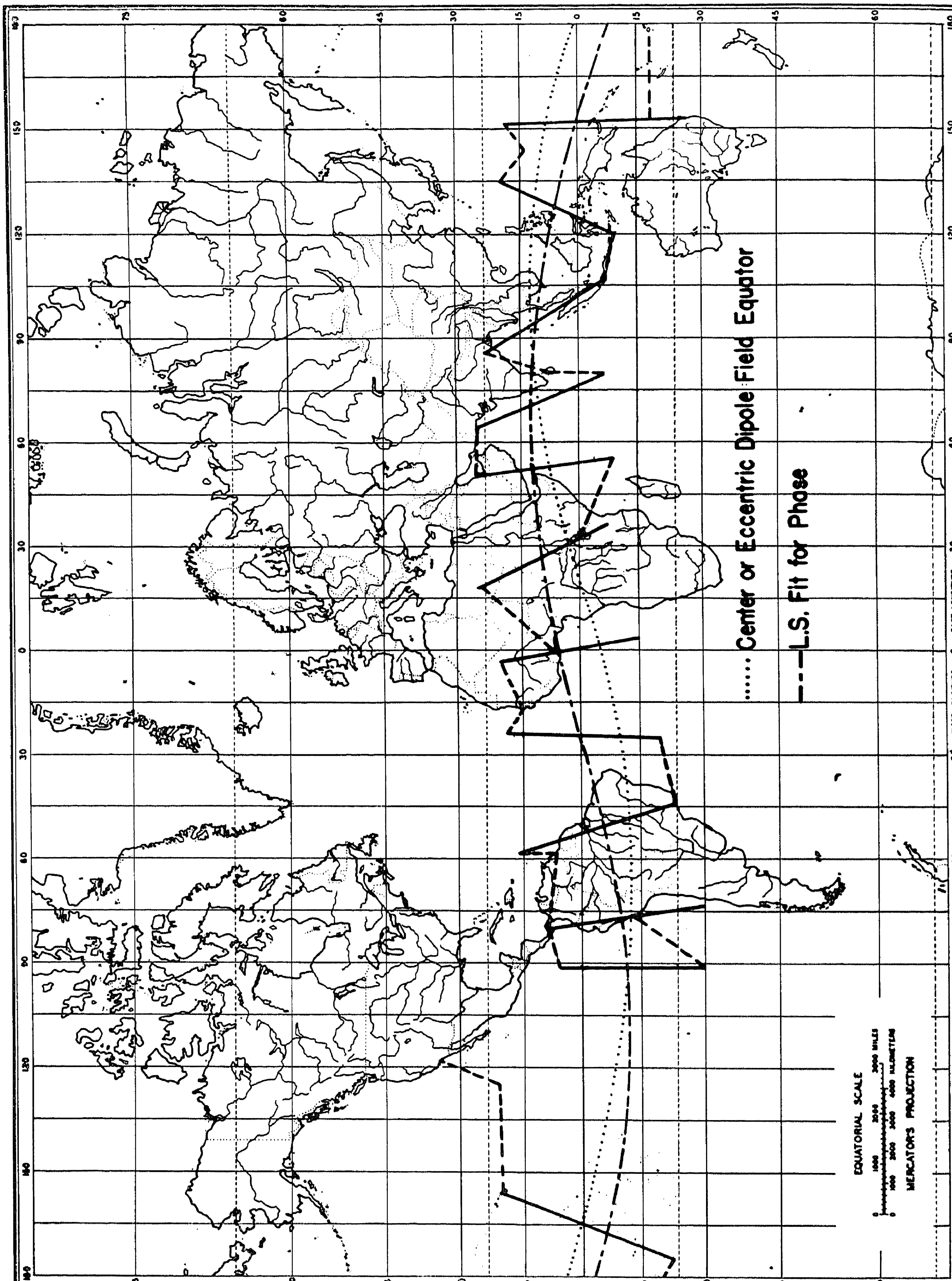

FIG. 1 — Route of aircraft carrying neutron intensity monitor at 18,000 ft pressure altitude; the solid line portions of the route correspond to the latitude curves shown in Figure 2

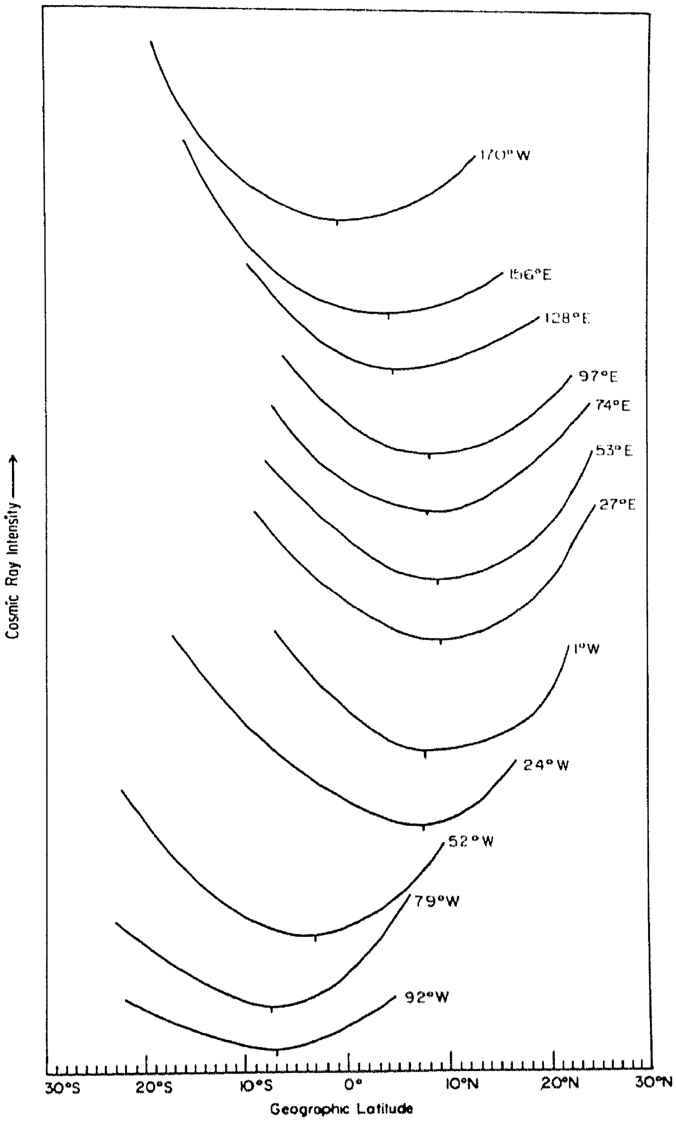

FIG. 2 — Latitude curves for the 12 equatorial crossings shown in Figure 1; these curves have not yet been corrected for the longitude effect

gives approximately 300 km as the separation of the magnetic and geoid centers.

(3) The peaks of the curve are displaced approximately 40° west of the cosmic-ray longitude curve predicted from the dipole terms of the spherical harmonic analysis, and in the direction of the maximum and minimum surface magnetic fields. It is interesting to note that these new results resolve the uncertainty in the longitude effect observed by *Vallarta* [1936].

The effective equator for cosmic rays—Measurement of the location of the minimum intensity depends to some extent upon the slopes of the latitude curves in Figure 2. The slopes are generally different in the two hemispheres; part of this asymmetry arises from the longitude effect introduced by crossing the equator obliquely (see Fig. 1). Although we have not yet corrected for this effect, the tentative location of minima shown in Figure 2 are plotted in Figure 4. A smooth curve was drawn to represent the principal features of the cosmic-ray equator derived from the new data. The amplitude shown in Figure 4 is substantially less than given by the geomagnetic dipole approximation. The intersections of the curve with the geographic equator are not 180° apart. If this curve were to represent the surface points common to a plane intersecting the Earth, then the results shown here imply that the equatorial plane of the magnetic field does not pass through the geoid center. In Figure 5 we show how this asymmetry in the mercator projection in Figure 4 might be represented. Of course, the representation of the data by a plane is rough, and Figure 5 is not to scale.

In Monograph No. 1 [*Simpson,* 1956] we showed how the cosmic-ray results compared with both the eccentric dipole field equator and the magnetic dip equator for the 1945 magnetic survey. In Figure 6 the same magnetic equator curves are shown for comparison with the new cosmic-ray data.

Returning to the three questions raised above, the new experimental results reported here show conclusively that the traditional description of the geomagnetic field by spherical harmonic analysis does not represent the field distribution which is effective for the deflection of cosmic-ray particles. It also appears that the observed surface magnetic fields near the equator, although in closer agreement with the location of the cosmic-ray equator, do not completely describe the effective field distribution. For example, the cosmic-ray equator appears to lie slightly west of the surface magnetic-field equator. However, the permanent field of the Earth should be described at distances beyond the surface of the Earth by an equator lying between the position of the surface equator and the geomagnetic-field equator, and not outside these limits, as we find for the cosmic-ray results. Thus, there remains the question of how important are external magnetic-field contributions which might be derived, for example, from the rotation of the Earth in an ionized medium.

Recently, *Rothwell* [in press] has suggested that only the surface magnetic field is important for determining the cosmic-ray intensity distribution, if one takes into account the 1955 mag-

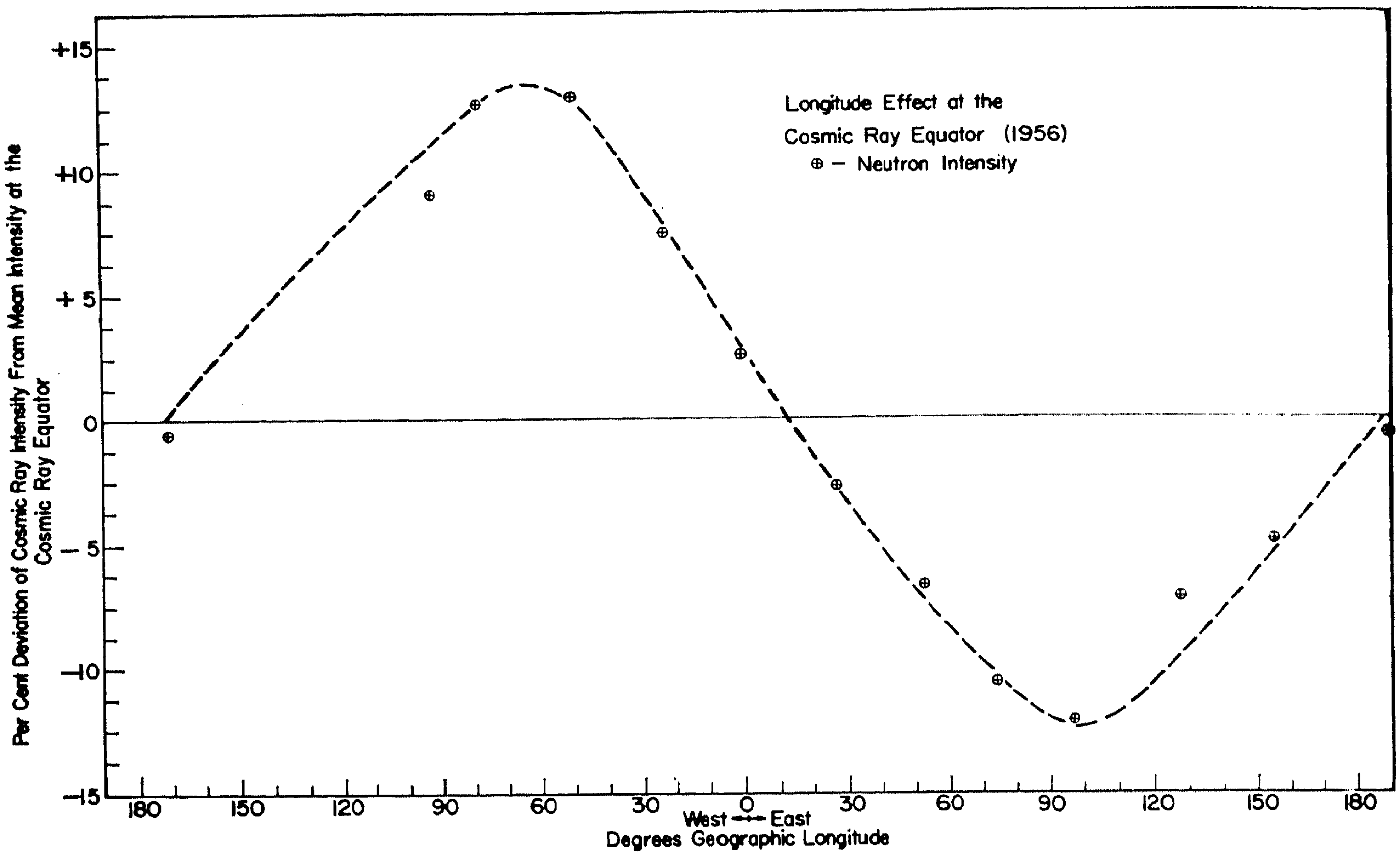

FIG. 3 — The longitude effect for the nucleonic component at the cosmic-ray equator

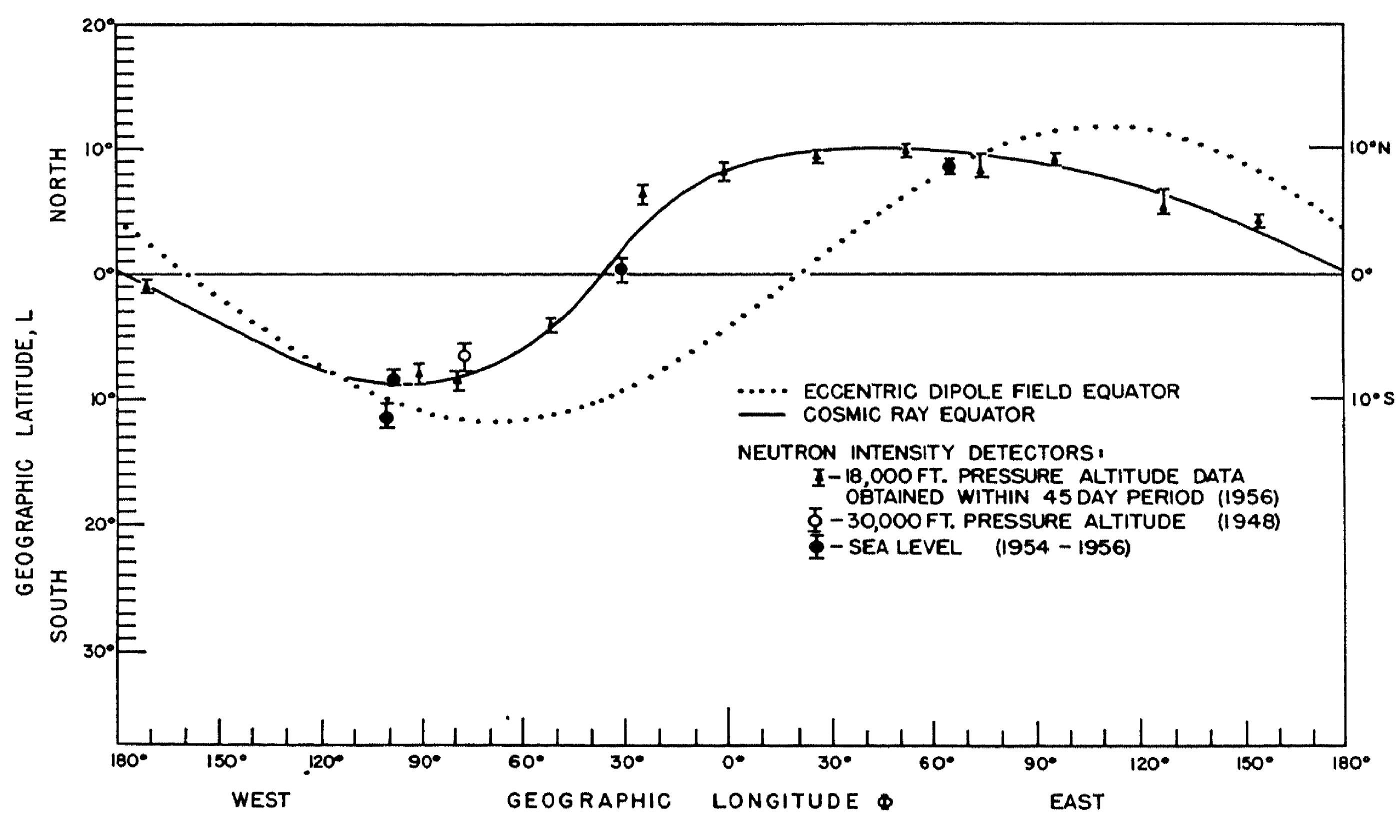

FIG. 4 — The smooth curve represents the cosmic-ray equator; experimental points have not been corrected for the longitude effect

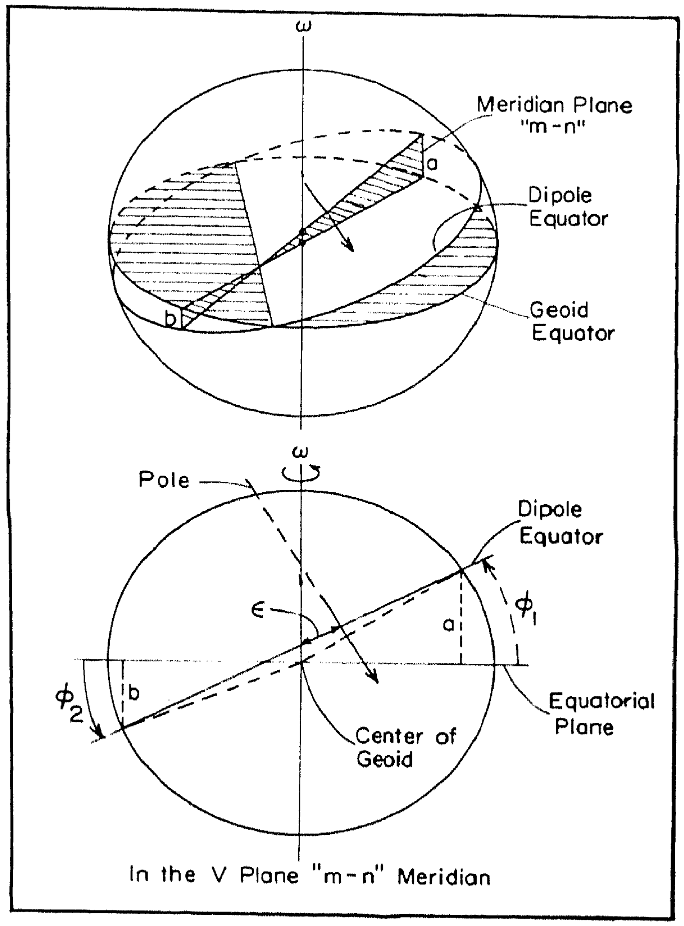

FIG. 5 — Schematic explanation (exaggerated scale) of the asymmetry of the cosmic-ray equator shown in Figure 4

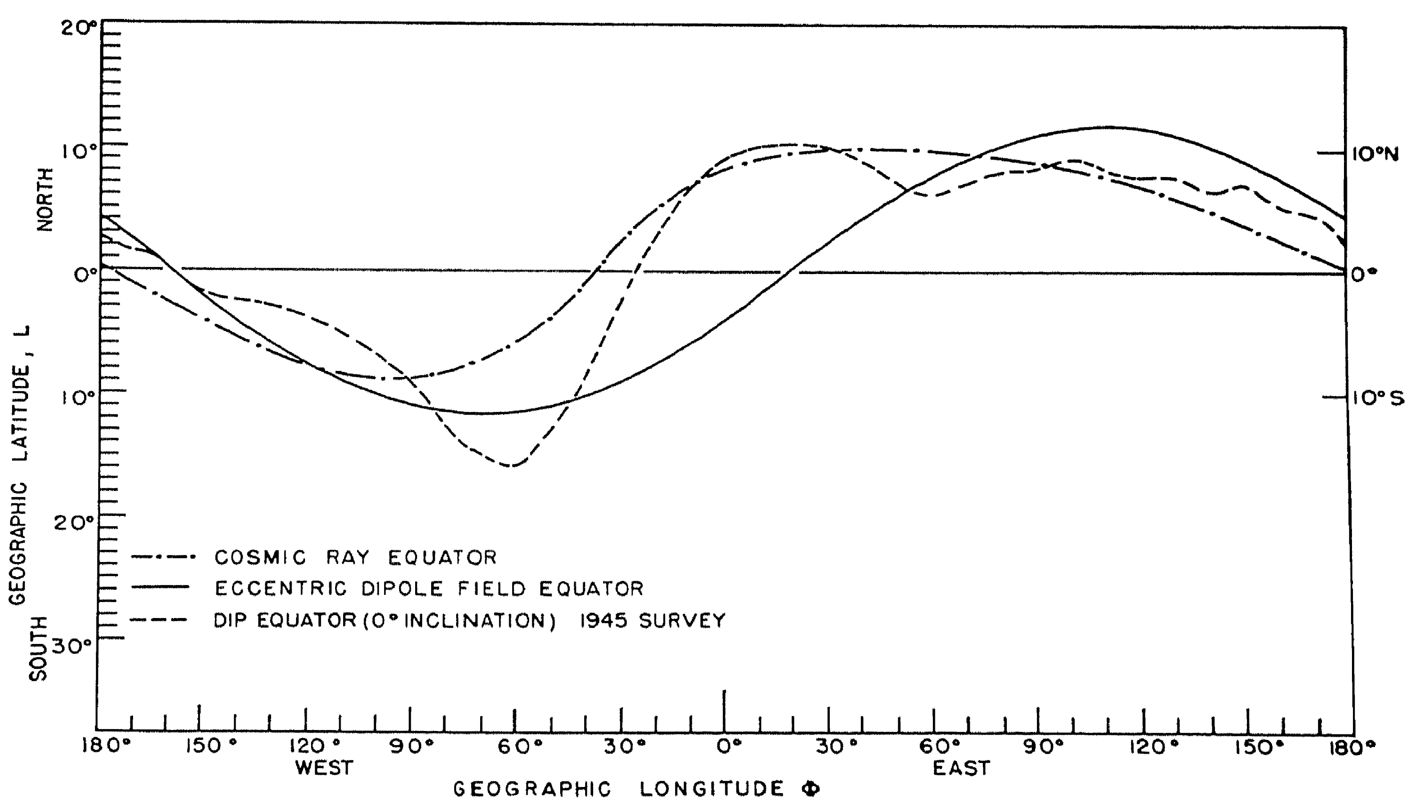

FIG. 6 — A comparison of the cosmic-ray, dipole, and dip equators

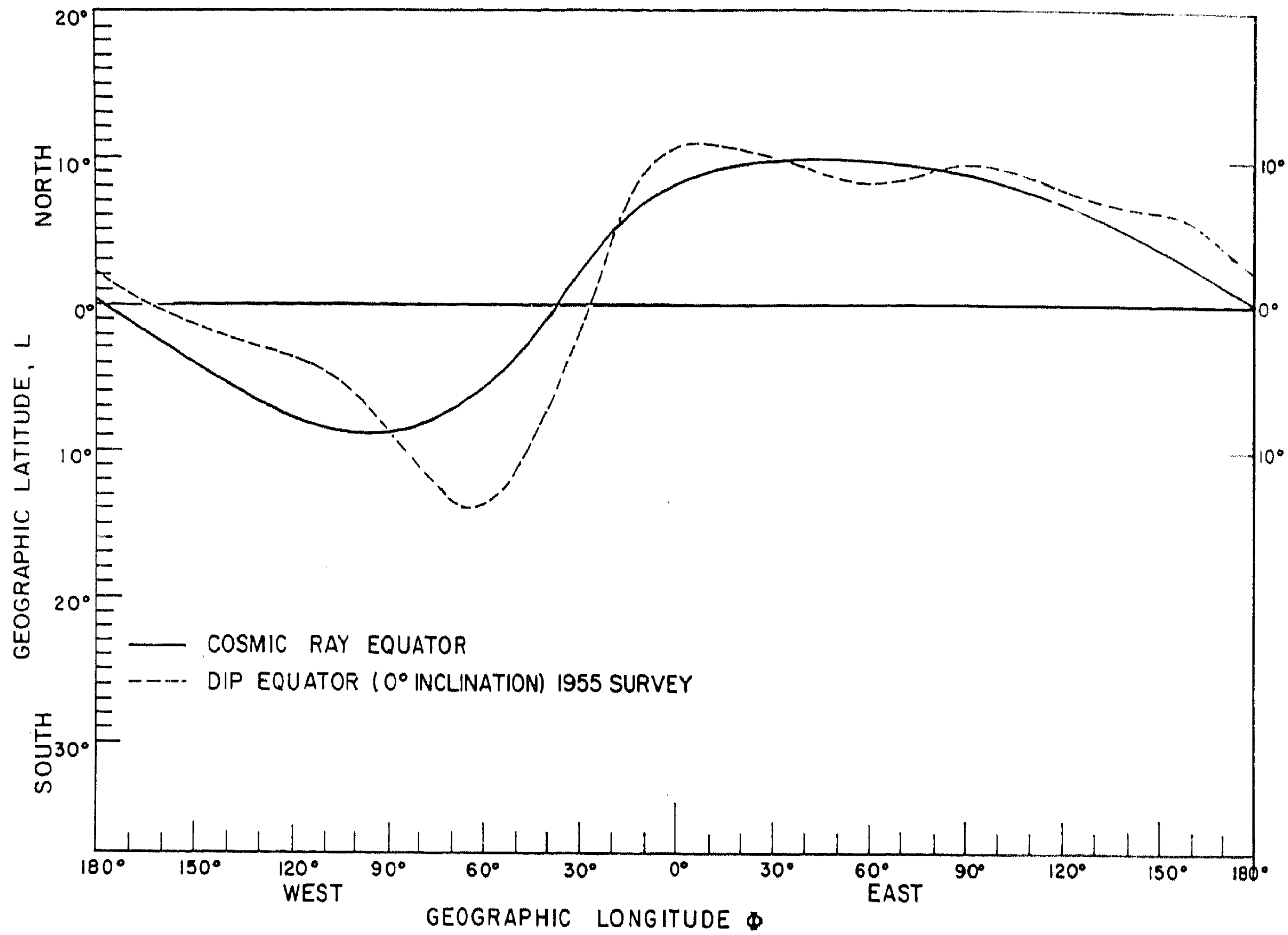

FIG. 7—A comparison of the preliminary cosmic-ray equator with the 1955 dip equator

netic equator instead of the 1945 dip equator. In order to compare our new cosmic-ray equator curve in Figure 4 with the 1955 dip equator, we have plotted this dip equator using coordinates published by the Hydrographic Office, U. S. Navy, which are almost identical with the Admiralty Charts used by Rothwell. The curves are compared in Figure 7.

Acknowledgments—It is a pleasure to thank the Strategic Air Command, U. S. Air Force, for their excellent support and assistance. The organization of the expedition by Major George J. Ott and his staff was deeply appreciated. This research was assisted in part by the Office of Scientific Research and the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, U. S. Air Force.

REFERENCES

KATZ, L., P. MEYER, AND J. A. SIMPSON, Further experiments in the geomagnetic field effective for cosmic rays, *Nuovo Cimento*, in press.

ROTHWELL, P., *Nuovo Cimento*, in press.

SIMPSON, J. A., Cosmic-ray experiments devised from recent U. S. Antarctic expeditions, *Geophys. Monogr. no. 1*, Amer. Geophys. Union (Nat. Acad. Sci. no. 462), 107–123, 1956.

VALLARTA, M. S., Longitude effect of cosmic radiation and the position of the Earth's magnetic centre, *Nature*, 139, 24–25, 1936.

Enrico Fermi Institute of Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois

Significance of Cosmic-Ray Monitor Observations

Robert L. Chasson

Introduction—In the past several years we have witnessed a major change of emphasis in the objectives of cosmic-ray studies. There is still much to learn about the composition and spectrum of the primary radiation and the details of its fate as well as of its progeny after it has entered the atmosphere. There is, however, substantial agreement that we now have a very adequate working knowledge of the radiation itself, making it possible to study it with the objective of ascertaining dynamic conditions in the interplanetary and, perhaps, galactic environment. This brings cosmic-ray studies into the realms of solar physics and astrophysics and may provide another way of investigating the material and electrodynamic conditions in cosmic space.

In this cosmic laboratory, time intervals of interest range from milli-millimicroseconds to billions of years, and transient phenomena, such as supernovae, give results that may be detectable for many millenia. We are anxious to establish the mechanism that gives rise to the cosmic radiation and how it is accelerated to its extremely high energy. These are primarily astrophysical problems, with cosmic rays seemingly a fortuitous phenomenon that may give better insight into the structure of the universe.

We have only a small flux of particles to study and must await the occurrence of interesting periodic and nonperiodic phenomena that may give clues to the origin of the radiation and the conditions of space within the accelerating and intervening regions. The best estimates give the mean energy density of cosmic rays in space as about equal to that of starlight, and we can observe on a continuous basis only the radiation that is able to reach us after coming through the great magnetic deflecting field of the Earth and is capable of yielding secondary particles that are energetic enough to penetrate at least through the atmosphere.

We exist near enough to the Sun to be able to sample low-energy cosmic rays leaving the Sun after they have traveled only a short distance and have not been able to experience interstellar accelerating processes during the transit. Such a location, on the other hand, results in a transient dilution factor that makes it more difficult to make reliable quantitative statements about the energetics and numbers of cosmic rays that have come from other sources within or outside of our galaxy. Recent and continuing studies by *Meyer, Parker,* and *Simpson* [1956] of the solar-produced radiation and the outside radiation as it is affected by the Sun are yielding fruitful results. There has been some success in the attempt to deduce from these observations various conditions in interplanetary space in which there seem to be transient turbulent magnetic fields (10^{-5} to 10^{-6} gauss) amid clouds of charged material particles. We hope to be able to infer eventually something about the nonsolar component, which composes the vast majority of the particles and contributes the high energy fraction of the cosmic rays reaching the Earth.

It is easiest to study the solar and solar-influenced cosmic rays because there are so many other direct quantitative and qualitative observations of solar behavior that lend themselves to correlation studies with cosmic-ray data. We have the flare patrol, sunspot count, coronograph, plage, magnetograph, radio noise, and other related solar data with which to work, and there is vigorous cooperative interaction between solar physicists and cosmic-ray observers. Such a possibility for correlation does not yet exist, other than by inference, with regard to our knowledge of the behavior-in-time of other stellar sources, of which the Sun may be a prototype.

Of similar importance in complete cosmic-ray studies are the results obtained by the meteorologists, geomagneticians, and those engaged in studies of the physics of the highest reaches of the upper atmosphere.

Some details of the experiments devised to study the solar component and the ensuing accomplishments will be discussed below. Also to be described are selected experiments designed to observe possible sidereal effects and general properties of the cosmic-ray flux as it is associated with other solar-geophysical phenomena.

General remarks concerning monitor experi-

ments—A monitor experiment is designed to operate for long uninterrupted periods of time and to record faithfully all fluctuations of cosmic-ray intensity. The data must then be studied for possible correlation with any evidence available from related cosmic-ray studies and all other types of astronomical, solar, and geophysical information gathered during the same epoch.

Such experiments of arbitrarily long duration comprise the static class of cosmic-ray studies. The dynamic class of experiments consists of observations of necessarily short duration, accomplished with the aid of rockets, balloons, and aircraft. Dynamic experiments are relatively free from the necessity for atmospheric corrections, a factor which is a normal complication of data obtained at fixed monitor stations, including those at mountain altitudes.

The following are the general types of instruments that are commonly used for cosmic-ray monitor purposes: (a) counter telescopes for detecting charged particles (Geiger-Müller counters, proportional counters, Cerenkov counters, and scintillation devices); (b) ionization chambers; (c) neutron detectors; (d) Wilson cloud chambers; and (e) nuclear emulsions.

The monitor measurement generally lends itself to the observation of unpredictable and important rare events and to the study of the systematics of the cosmic-ray flux. Data of high statistical quality are secured because of the long duration and almost arbitrarily large size of the experiments. Since, however, the experiments are confined to locations relatively deep in the atmosphere, one may not use them for direct observation of primary effects but must look at the secondary products and extrapolate their fluctuations back to primary fluctuations by means of our knowledge of the detailed behavior of the generations of particles composing the atmospheric cascade. Only the dynamic experiments give the possibility of satisfactory observation of the behavior of the primaries before they have penetrated very deep into the atmosphere. The statistical quality, however, is somewhat reduced by the shortness of operable time and generally small size of the recorders. Satellite observations will bridge the gap caused by the limitations inherent in each of the two existing classes of experiments.

Already in effect and planned more extensively for IGY are cooperative alert systems that make possible the strategic triggering of special dynamic experiments during times when the monitors detect unusual events. There are also interim dynamic experiments which will serve as controls and provide continuity in the search for changes and the causes of change of the primary spectrum and flux of cosmic radiation.

The problem of meteorological effects—An extremely important and independent factor affecting the intensity of cosmic radiation, as observed at appreciable depths in the atmosphere, is the air mass distribution and the complex of meteorological changes. The geomagnetic field serves to control the primary flux reaching the top of the atmosphere, but to understand the radiation observed near the surface of the Earth, it is necessary first of all to study the fluctuations that occur during solar and geomagnetic stable periods; these then are correlated practically exclusively with meteorological changes. A great deal of work has been done throughout the history of cosmic-ray research to correlate intensity changes with barometric pressure fluctuations, atmospheric temperature and mass distribution changes, and fluctuations of the altitude of various upper-atmospheric constant-pressure levels. The correlations are by no means complete nor have there been devised completely satisfactory ways of correcting the cosmic-ray data for these atmospheric influences.

The ideal is to obtain an unambiguous correction system that, after application to the raw data, would leave a record whose fluctuations reflected completely those experienced by the parent primary radiation. This goal is reached rather easily where the low-energy nucleonic component is being counted; unstable particles are not observed in such experiments and, therefore, only a simple barometric correction is required. Absorption proportional to the total mass of air above the detector is thereby taken into account.

To observe charged particles and then to correct the record for atmospheric changes calls for an extensive set of calculations that somehow takes into account mass absorption changes as well as fluctuations introduced by changing the relative importance of radioactive decay effects and the probability of collisions that lead to unstable meson production. Changes of intensity associated with such stochastic processes are explained primarily in terms of changes of atmospheric mass distribution.

The extent to which the meteorological effects can be eliminated at the present time is limited by the accuracy of available radiosonde data. Also, in order to be able to apply complete atmospheric corrections (other than simple barometric) to monitor data, at least four or perhaps six radiosondes must be flown per day in the vicinity of the cosmic-ray station. Such extensive local meteorological observations are not presently available near most cosmic-ray stations.

In Figure 1 [*Chasson* and *French*, 1955] may be seen the effect of applying various statistical systems of meteorological corrections [*Duperier*, 1949] to 79 cosmic-ray datum periods selected from geomagnetically quiet times. The percentage deviation from the mean intensity of the group is plotted, with the raw data appearing in the top graph. The measurements, of mu mesons that were able to penetrate through 20 cm of lead absorber, were made at Lincoln, Nebraska, 52° N geomagnetic latitude, at an altitude of 350 m above sea level. Succeeding graphs express the smoothing due to the application of correction factors that included the following groups of terms: 1B, barometric pressure; 2B, barometric pressure, height of 100-mb level; 3B, barometric pressure, height of 100-mb level, mean temperature in region between 100-mb and 200-mb levels; and 4B, barometric pressure, height of 50-mb level, mean temperature in region between 50-mb and 200-mb levels.

Subsequent work has shown that the smoothing effect is practically indifferent to the empirical correction parameters used if at least three are included in the analysis; seemingly required are barometric pressure, some reference height at or above the tropopause, and some reference temperature. The physical validity of the various correction models is not equal, however, and the results of the regression analyses show greater and greater internal consistency as higher and higher regions of the atmosphere are considered.

Other correction methods have been devised [*Dorman* and *Feinberg*, 1955; *Olbert*, 1953] which are based on a phenomenological model of the cosmic-ray cascade in the atmosphere, but their complexity does not lend them easily to a practical application of any extensive nature. For most practical purposes the statistical technique of meteorological corrections is apparently adequate. In contrast, however, a thorough understanding of the mechanism of the solar diurnal variation (0.2 pct amplitude) requires a correction system that has considerably more accuracy and is made on a detailed physical basis.

Summary of important time and spatial variations of cosmic-ray intensity—Several types of cosmic-ray variations have been discovered that depend upon time or location or both: (a) nonperiodic variations which include geomagnetic storm (Forbush) decreases, meteorological effects, and solar-flare increases; (b) periodic time variations which include 27-day recurrence tendency, solar diurnal effects, semi-diurnal effects, seasonal effects, annual effects, and sidereal diurnal effects; and (c) spatial variations which include latitude effect, longitude effect, zenith-

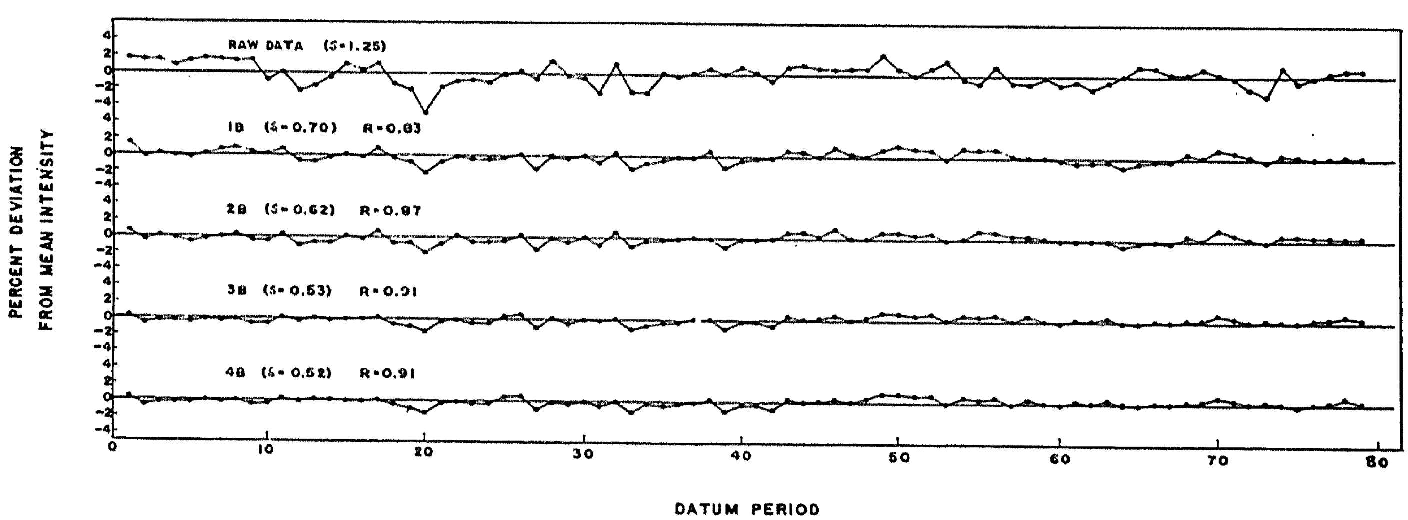

FIG. 1 — Smoothing of fluctuations of the penetrating component of cosmic radiation near sea level achieved by application of various schemes of statistical corrections for meteorological effects [*Chasson* and *French*, 1955]; S is the standard deviation of points of the group and R is the multiple correlation coefficient

angle effect, altitude dependence, and east-west asymmetry.

These spatial variations are found to be time dependent also; the time variation of the latitude effect is especially important in the study of the allowed primary spectrum and its relationship to solar activity [*Meyer* and *Simpson,* 1954]. Time variations also have spatial fluctuations.

It must be emphasized that the list given above is one of operational convenience and that many of the 'different' effects are associated with one another. They are, in various ways, manifestations of interaction of the radiation with matter and with changing local and remote electric and magnetic fields. They are subject to fluctuations of source strength and distribution, and they depend especially upon the charge and momentum spectrum of the radiation, which may vary with time and position. All of them are subject to an intensive worldwide check during IGY.

The seasonal and solar diurnal variations have been linked largely to atmospheric causes. The annual variation corresponds with that of the geomagnetic field strength; annual variations of intensity in the north and south geomagnetic hemispheres are in opposite phase. The semidiurnal wave is attributed largely to a nonisotropic primary distribution. The zenith-angle effect and altitude dependence are due to atmospheric absorption and its relation to production and loss of secondary particles in the atmosphere.

Some present considerations derived from monitor studies—Monitor studies over the past twenty years have given strong indications that the primary intensity is relatively independent of time and that the spatial distribution of particle trajectories is virtually isotropic. Such deductions are possible only after accounting, at least in part, for fluctuations arising from meteorological causes. The essential isotropy itself is deduced from the success of the Lemaître-Vallarta theory and its extensions in explaining the observed dependence of intensity upon geomagnetic coordinates.

Isotropy and time independence would be characteristic of radiation having a general galactic origin since it seems plausible for such special conditions to exist only if the radiation is born far enough away to have spent of the order of a million years in reaching us, providing an essential storage of particles within the galaxy. Thus, after leaving the source, the direction of the particles would be randomized by collisions with interstellar matter and with widely scattered but extensive weak magnetic fields. The sources are assumed to be distributed rather uniformly within the galaxy. Isotropy and time independence are idealizations, the very violations of which present us with some of the most interesting and important bits of information concerning the general role of cosmic rays in nature.

For example, there is tentative evidence that strong extragalactic sources may exist, as deduced from the observation of extensive showers of particles with a total energy of the order of 10^{18} to 10^{19} e v [*Clark* and others, 1957]. It is considered that such energies as these could not be imparted to particles confined within our visible galaxy, assuming that magnetic fields are responsible for the accelerations and storage of particles in the galaxy [*Fermi,* 1949, 1954; *Morrison, Olbert,* and *Rossi,* 1954; *Parker,* 1957]. Then they must have come from an extragalactic source or from some portion of our galaxy lying outside the visible disc. In support of the latter possibility, there is radioastronomical evidence for a gas corona surrounding the galactic disc [see *Burbidge,* 1956, for references]. If the extragalactic alternative is not accepted, then the assumption that the Sun is a prototype source must perhaps be modified. Such a corona would conceivably contain transient weakly magnetized clouds of ionized material affording a vastly increased intragalactic space for acceleration to extremely high energy and storage of cosmic rays produced initially within the galaxy. The question is an open one, and it should be remarked also that the assumption of extragalactic sources leads to an expectation of anisotropy, particularly at extremely high energies.

There is some substantial direct evidence that the radiation is not completely isotropic. A small, but apparently statistically real, sidereal diurnal variation has been observed, as is shown in Figure 2 [*Lange* and *Forbush,* 1948; *Elliot* and *Dolbear,* 1951]. These observations were made during a period of low solar activity; Elliot and Dolbear plotted sidereal time-dependent differences between simultaneous recordings of a north-pointing counter telescope, which essentially aimed constantly at one part of the celestial sphere, and a telescope whose axis was at 90° to that of the first one and thus swept approximately through a celestial great circle as the

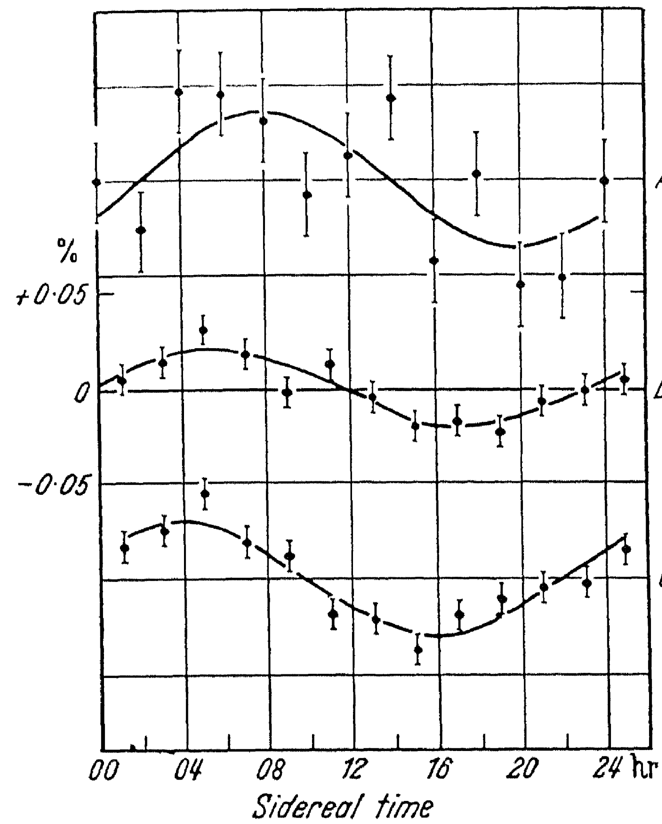

FIG. 2 — Sidereal diurnal variation; curve A is south minus north variation [*Elliot* and *Dolbear*, 1951]; curve B results from combining ionization chamber data taken in the northern and southern hemispheres, thus eliminating a spurious effect introduced by seasonal changes in amplitude and phase of the solar daily variation; curve C is from ionization chamber data taken near the geomagnetic equator, where seasonal changes of the solar daily variation should be small [*Lange* and *Forbush*, 1948]

Earth turned on its axis. The complications of having to make atmospheric corrections were avoided in this work. The Lange-Forbush experiments were done with Carnegie ionization chambers shielded with 12 cm of lead, with corrections for annual variation applied between the two sets of high-latitude data. Uncertainty of the reality of this effect is traced to the possible introduction of a spurious sidereal diurnal variation that results from regular seasonal changes, both in amplitude and phase, of the solar daily variation. Such an apparent sidereal effect can appear when the data from a single station are averaged over a whole year.

Further evidence of possible departure from isotropy is gained from the observation of a small but significant variation of the intensity of extremely high-energy particles when studied with respect to the direction of view into the celestial sphere [*Sekido, Yoshida,* and *Kamiya,* 1956]. The trajectories of such particles would be relatively free of geomagnetic field deflection, and the measurements were made at 80° zenith angle to insure that field-sensitive particles were absent from the data collected. This is an example of exploiting atmospheric absorption effects to give data of greater purity, although the counting rate of the Sekido experiment was exceedingly low. Diffusion of source direction is caused by encounters of the observed particles with weak interstellar magnetic fields. There is some ambiguity in the results obtained thus far, however, and these studies continue with further refinements of techniques. If they are unambiguously established, these two sidereal effects would be especially indicative of the possible existence of strong galactic 'point' sources of cosmic radiation (for example, Crab Nebula?).

A third possible indication of anisotropy is the variation with the solar cycle of the east-west asymmetry of the penetrating radiation at high latitudes as shown in Figure 3 [*Jacklyn* and *Fenton,* 1957]. From the original observations of the east-west asymmetry, in conjunction with the Lemaître-Vallarta theory of the allowed cone of radiation, it was deduced that most, if not all, of the primary charged-particle cosmic radiation was positively charged. This conclu-

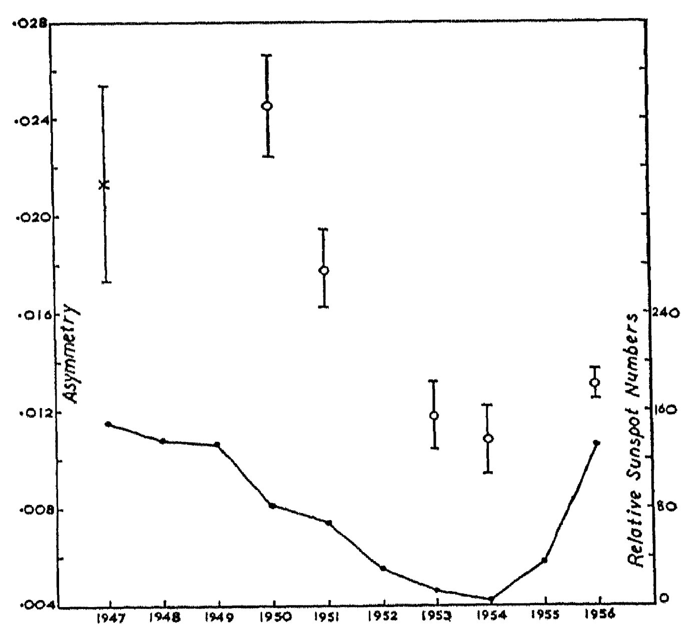

FIG. 3 — Variation of east-west asymmetry at high latitude; circles represent the asymmetry for the observing period in each year, with standard deviations [*Jacklyn* and *Fenton,* 1957]; solid points (connected) indicate the Zurich annual mean relative sunspot number

sion has since been abundantly verified by direct observation of primaries in dynamic experiments. If the radiation were isotropic, one would not expect the east-west asymmetry to vary with solar activity although absolute intensities would change due to changes of interplanetary material and magnetic screening conditions. The superposition of an anisotropic primary component of variable intensity would have an asymmetrical effect at the recorder.

Departures from time independence on a short time scale are much easier to observe, and they occur with periodic, quasi-periodic, and random character. A most important random change that has been seen (only five times in the history of cosmic-ray studies and most recently on February 23, 1956) is the sharp increase of intensity occurring in conjunction with great solar flares. That the Sun is a source of cosmic rays, if not the only type of source in existence, is clear from these infrequent phenomena. The increases of intensity of the low-energy nucleonic component are greatly in excess of those observed simultaneously for the high-energy radiation; the ratios between the changes of the two components have ranged as high as two orders of magnitude. Also, the spectrum of the flare particle radiation is much steeper than the spectrum observed during ordinary times.

Figure 4 is the record made at Chicago [*Meyer, Parker, and Simpson,* 1956] of the fluctuations of the low-energy nucleonic (solar) component during the epoch of the great solar flare of February 23, 1956. The observations were made with a Simpson neutron monitor pile, which is a means of counting neutrons coming from nuclear evaporation stars produced in the pile materials (a lattic of lead with paraffin moderator) by incoming neutrons, protons, and a few pi-mesons. Latitude and longitude studies have been made of this flare effect, enabling the calculation of the flare-particle spectrum and comparison with calculated trajectories of solar produced cosmic rays [see *Lüst,* 1957, for references].

The postflare trend has been analyzed with

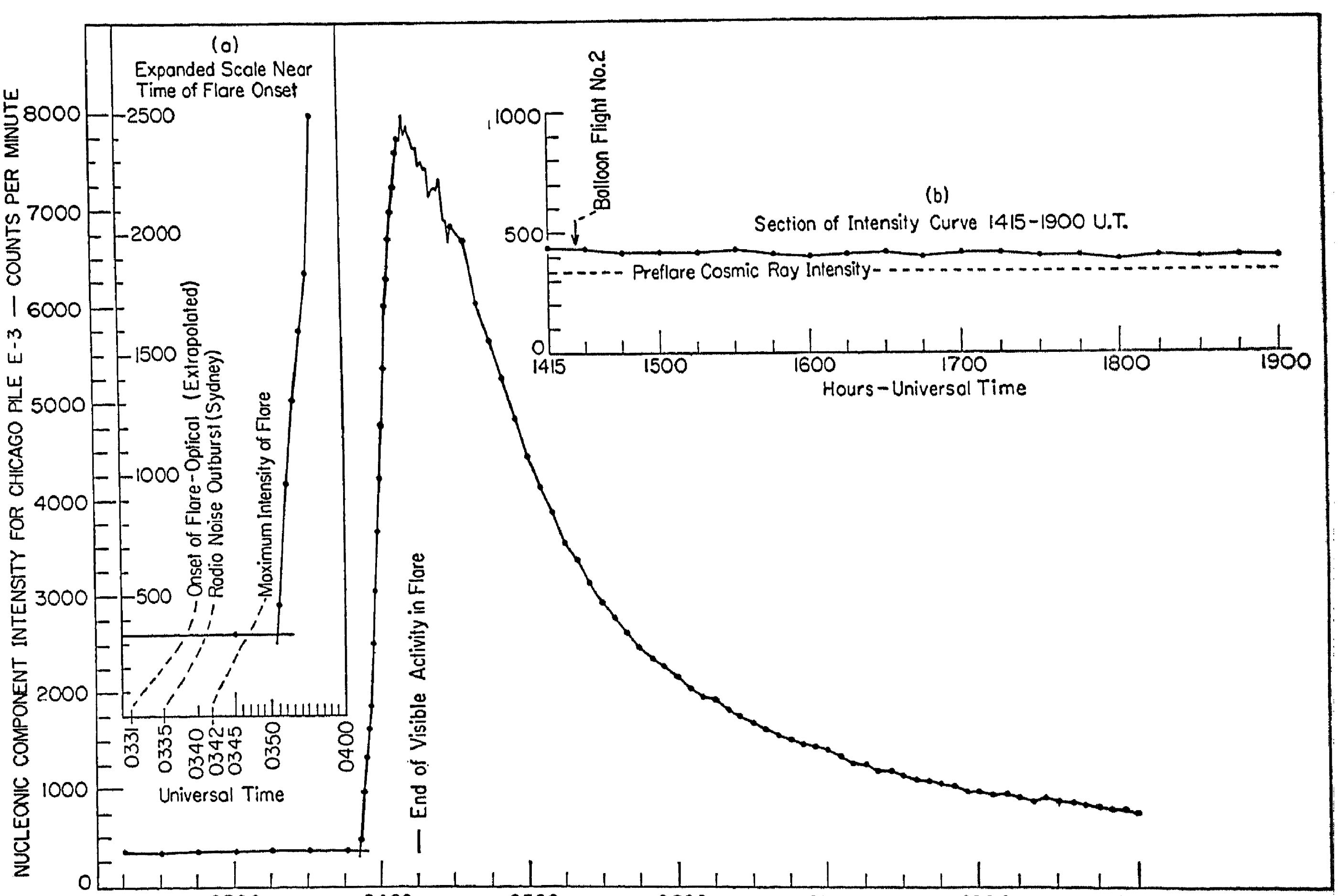

FIG. 4 — Increase of low-energy nucleonic component of cosmic rays measured at Chicago during the solar flare of February 23, 1956 [*Meyer, Parker,* and *Simpson,* 1956]

respect to the alteration of conditions in interplanetary space in relation to solar activity: screening and albedo effects imposed upon the lower-energy solar cosmic rays. Such effects arise from the emanation of large quantities of charged debris from the disturbed regions of the Sun, carrying along tangled magnetic fields. The time dependence is explained by the migration of the clouds away from the Sun, with the eventual transient permeation of the interplanetary space with the charged, magnetized material [*Meyer, Parker,* and *Simpson,* 1956; unpublished work of Morrison, Gold, Hayakawa, and Cocconi]. There is considerable uncertainty regarding the persistence of the state of disorder of these clouds as they migrate away from the Sun.

Beside these rare solar-flare events, regular and quasi-regular time variations have been correlated with solar activity and associated geomagnetic disturbances. Such effects seem to stem from the same general mechanism that would explain the tail of the solar flare trace seen in Figure 4; it is, namely, a fluctuating modulation or screening or trapping of the incoming galactic cosmic-ray beam by alteration of electromagnetic and material conditions existing in the local space available to streams or clouds of solar produced ionic and particle debris. Figure 5 shows such a solar induced modulation as it is manifested in the 27-day recurrence tendency [*Meyer* and *Simpson* (Forbush), 1954]. It is seen that the amplitude of the 27-day variation changes almost synchronously with the sunspot number and exhibits the well known 11-year periodicity characteristic of solar activity. The trend shown in

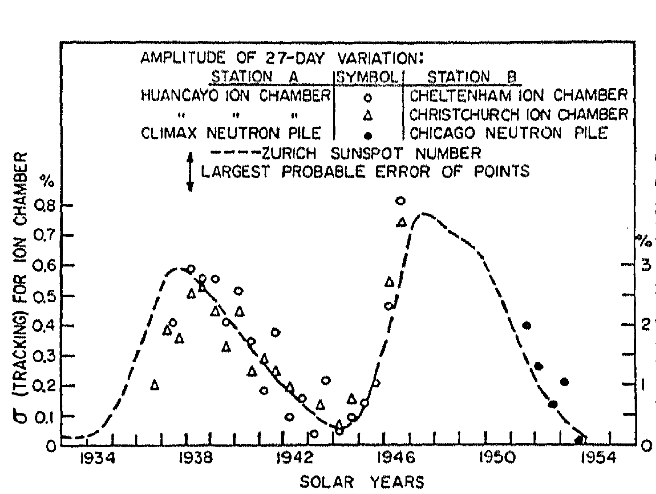

FIG. 5 — Time dependence of the amplitude of the 27-day recurrence tendency from revised analysis of Forbush ionization chamber data and neutron monitor data [*Meyer* and *Simpson,* 1954]

this figure has continued to date, but the 27-day recurrence tendency is most pronounced when the Sun is in an especially disturbed condition. Such was the state of affairs during the several months period bracketing the time of the great solar-flare event of February 23, 1956. A maximum effective partial screening of the incoming nonsolar cosmic rays is achieved when the source of the clouds is on the visible hemisphere of the Sun and the debris is preferentially emitted into the region of space between Sun and Earth. Thus a 27-day periodicity would be expected, corresponding with the solar synodic rotation period, and the periodicity would appear markedly only during times of appreciable solar activity. Overlapping of 27-day variation cycles has been observed, as would be expected during times when there is in existence more than one great solar active region.

Confirmation that active solar regions affecting cosmic rays are of a special nature (the strong unipolar M-regions first postulated by Bartels to relate solar activity to geomagnetic storminess) is found in the results obtained by means of the remarkable solar magnetographic technique developed by Babcock and Babcock. The magnetograph results indicate that normal solar activity does not cause appreciable changes in terrestrial cosmic-ray intensity. A question that has yet to be completely answered is connected with the intrinsic nature of the 27-day phenomenon: Is the variation an addition to, a subtraction from, or a modulation about some level or average intensity? The best evidence thus far seems to favor the subtraction explanation.

A rather clearcut species of screening effect is the Forbush type of worldwide intensity decrease observed to occur in association with some periods of geomagnetic storminess. Such cosmic-ray decreases may have several initial characteristics; they may begin suddenly or slowly, and the onset may occur simultaneously with, before, or after the advent of a detectable geomagnetic storm. The magnitude of the decrease and its starting characteristics are not related in any particular way to the amplitude or the type of commencement of the storm, and in about 80 pct of the cases of serious geomagnetic field disturbance, the cosmic rays do not show any detectable change. In cases of Forbush decreases, the recovery to normal cosmic-ray intensity may

take many days or weeks, depending upon the disturbed condition of the Sun. Examples of prestorm cosmic-ray decreases, including an event with a sharp front and one with a gradual front, may be seen in Figure 6 [*Chasson,* 1954]. These data were taken with a counter telescope accepting the penetrating radiation. The effects were much more pronounced in neutron monitor recordings.

It was formerly thought that the Forbush effect could be explained by an alteration of the Lemaître-Vallarta allowed cone possibly caused by augmentation of ring currents flowing in the equatorial plane of the Earth and having ring radii several times that of the Earth [*Chapman,* 1937]. The alteration of the magnetic dipole field so produced could conceivably affect the allowed entry of cosmic rays, and the ring-current model has been quite successful in explaining auroral phenomena. Detailed calculations [*Treiman,* 1953; *Hayakawa* and others, 1950] have shown, however, that the ring-current theory and reasonable modifications of it would predict the wrong sign or too small a magnitude for the cosmic-ray effect at intermediate latitudes. The screening hypothesis, in which the charged magnetized clouds of solar debris will deflect or trap cosmic rays approaching the Earth, offers a more plausible and consistent explanation for the Forbush effect; furthermore, the flexibility of the possible spatial distribution of the clouds both at source and within the interplanetary region, lends itself to explaining the various manifestations of start and trend of Forbush decreases, including geomagnetic events with which there are associated no detectable cosmic-ray effects.

It is difficult to guess as to the full implications of the few studies described so briefly above, but it is quite clear that there is much to learn, via cosmic rays, regarding the systematics of stellar and interstellar processes.

Cosmic-ray monitor studies during the IGY—The cosmic-ray monitor experiments that are in operation during IGY are largely improved versions of well-established monitor experiments that have operated successfully for many years. One of the most important special developments has been the standardization of basic types of equipment for worldwide observation. The effect will be to minimize ambiguity in making comparisons amongst basic data taken at the various

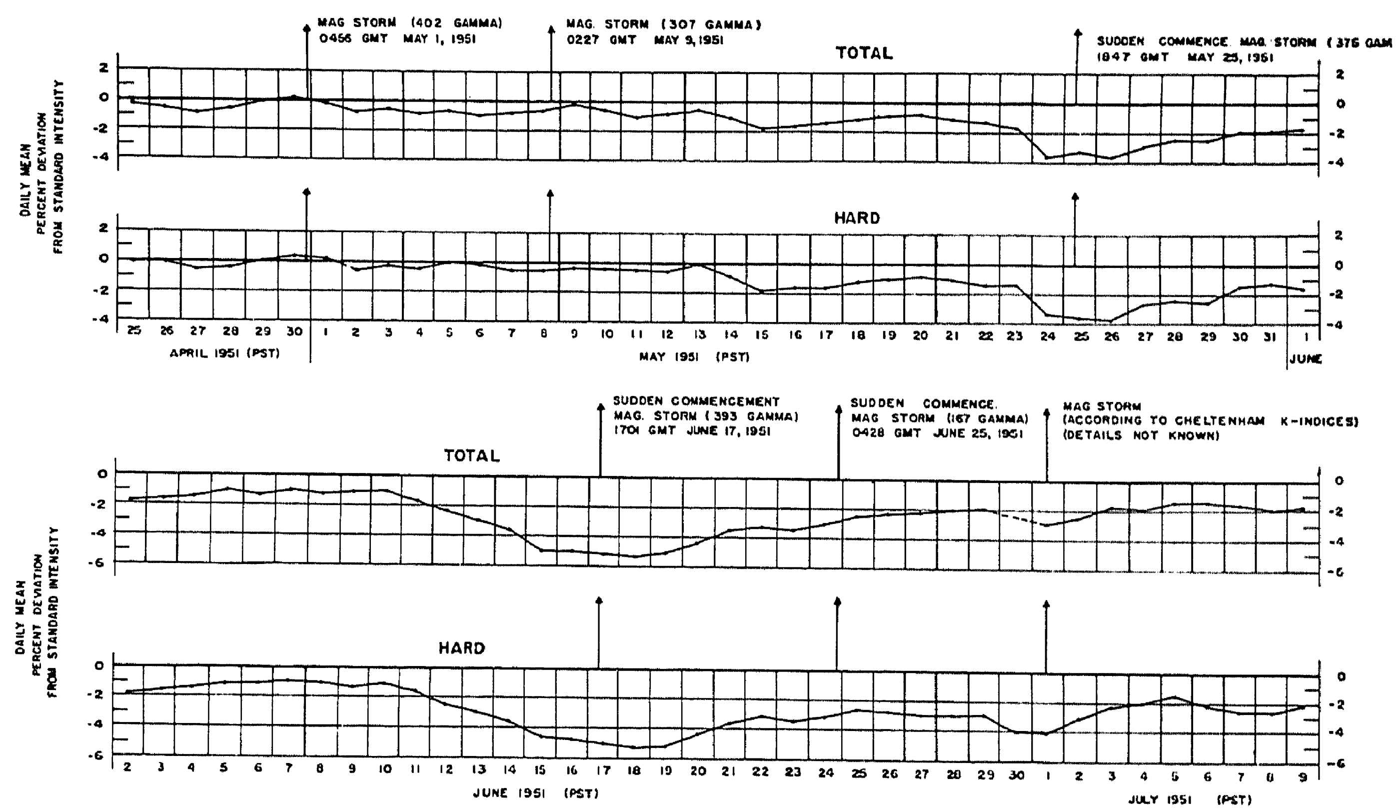

FIG. 6 — Magnetic storm decreases of the penetrating component (Forbush effect) accompanying the great sunspot activity of May and June, 1951; variation of the character of the beginning of the cosmic-ray storm may be seen as well as its variability with respect to the time of onset of the measurable geomagnetic disturbance. Some 27-day wave characteristics may also be seen [*Chasson,* 1954]

stations. Lack of standardization in pre-IGY studies, except for that achieved privately amongst small cooperative groups, has been a constant handicap in studies of worldwide effects. Standardization of cosmic-ray equipment for IGY has been achieved largely as a result of longtime studies of the Sub-Committee on Cosmic Ray Intensity Variations of the Cosmic Ray Commission of the International Union of Pure and Applied Physics.

There are essentially two types of standard equipment: (a) triple coincidence counter telescope (10 cm lead absorber) with cubical geometry and minimum prescribed counting rate and sensitivity for detection of penetrating particles (mesons); and (b) neutron monitor pile (Chicago design) for detection of the low-energy nucleonic component. The neutron monitor arrangement at the University of Nebraska consists of six boron trifluoride (enriched) neutron counters immersed in a latticework of lead and paraffin. Three of the counters feed one electronic registration system, and the other three feed a second system, thus giving two sets of independent data. A central electronics rack contains a master time control for data recording, electromechanical controls for adjusting the data-recording time interval and count scaling ratio during epochs of unusual intensity fluctuations (for example, solar flare and geomagnetic-storm effects), and a precision differential counting rate meter which is used to provide a written record (on a recording meter) of departures from average intensity. There is also another rate meter which serves as detector of unusual events and, consequently, to control the electromechanical alarm system.

Cosmic-ray monitor observations for the official IGY program are by no means limited to the standard ones. In addition to the neutron monitors and cubical meson telescopes, there are ionization chambers, shower detectors, counter telescopes for deep underground studies of the very high energy particles, vertical narrow-angle counter telescopes, east-west and north-south tilted telescopes, and several shipboard experiments to complement those at fixed stations.

Figure 7 is a photograph of a multiple meson

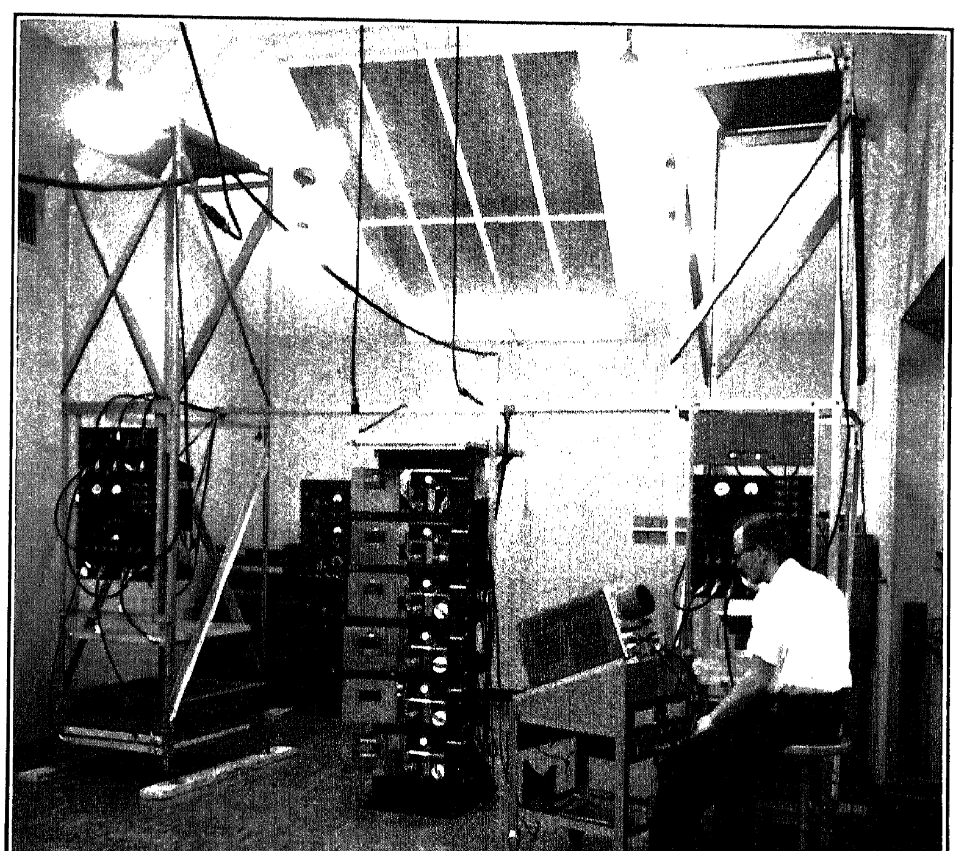

FIG. 7 — Array of IGY meson telescopes, with associated equipment, including two standard cubical telescopes, two vertical narrow-angle telescopes, and an east-west pair of narrow-angle telescopes (University of Nebraska)

telescope arrangement (University of Nebraska). At the bottoms of the two metal towers are seen the three counter trays of the international standard cubical telescopes. At the top of each tower is another counter tray which acts in coincidence with the bottom three to give, in each framework, a vertical narrow angle fourfold coincidence telescope (10° opening angle to zenith). Between the towers is an additional tray which acts in coincidence with the top tray of one tower and the bottom tray of the other, giving two narrow-angle tilted telescopes that lie in the geomagnetic east-west plane. The axes of these two telescopes are at 45° to zenith. In the left background is seen equipment which will be used as an unshielded wide-angle counter telescope to measure fluctuations of the total meson intensity.

As indicated previously, the primary objective of the IGY cosmic-ray monitor program is to make a synoptic study on a worldwide basis of the systematics of the cosmic-ray flux, both in time and in space, as it reaches the Earth. Standardization of equipment affords a means to make unambiguous comparison of results received simultaneously at different locations, and accompanying special experiments provide an opportunity to make simultaneous concentrated studies of particular facets of the cosmic-ray geophysical problem.

It is thus to be hoped that there will be achieved a durable and reliable continuing system of cosmic-ray studies that will serve a primary function in the group of fundamental geophysical and extrageophysical scientific disciplines.

Acknowledgments—The author is deeply grateful for the encouragement and support accorded to him by the United States National Committee for the International Geophysical Year. He would also like to thank the Research Council of the University of Nebraska for grants in support of work which led to participation in IGY and for later equipment grants made to permit the inclusion of narrow-angle telescopes in the IGY meson work. Construction of the new laboratory for the IGY work was made possible through funds allocated from the proceeds of the State of Nebraska Institutional Building Levy.

REFERENCES

BURBIDGE, G. R., The halo distribution of radio emission and extended magnetic fields in our galaxy and M31, *Astrophys. J.*, **123**, 178–181, 1956.

CHAPMAN, SYDNEY, Cosmic rays and magnetic storms, *Nature*, **140**, 423–424, 1937.

CHASSON, R. L., Cosmic-ray intensity fluctuations at sea level, *Phys. Rev.*, **96**, 1116–1123, 1954.

CHASSON, R. L., AND W. R. FRENCH, JR., Meteorological effects for cosmic-ray mu mesons at sea level, *Proc. Int. Cosmic Ray Conf.*, (unpublished) Guanajuato, Mexico, 1955.

CLARK, G., J. EARL, W. KRAUSHAAR, J. LINSLEY, B. ROSSI, AND F. SCHERB, An experiment on air showers produced by high-energy cosmic rays, *Nature*, **180**, 353–356 and 406–409, 1957.

DORMAN, L. I., AND E. L. FEINBERG, Survey of work done in USSR regarding atmospheric effects on cosmic radiation, *Proc. Int. Cosmic Ray Conf.*, (unpublished) Guanajuato, Mexico, 1955.

DUPERIER, A., The meson intensity at the surface of the Earth and the temperature at the production level, *Proc. Phys. Soc.*, A, **62**, 684–696, 1949.

ELLIOT, H., AND D. W. N. DOLBEAR, Directional measurements of the diurnal variation of cosmic ray intensity, *J. Atmos. Terr. Phys.*, **1**, 205–211, 1951.

FERMI, E., On the origin of cosmic radiation, *Phys. Rev.*, **75**, 1169–1174, 1949.

FERMI, E., Galactic magnetic fields and the origin of cosmic radiation, *Astrophys. J.*, **119**, 1–6, 1954.

HAYAKAWA, S., J. NISHIMURA, T. NAGATA, AND M. SUGIURA, The effect of the equatorial ring current on cosmic-ray intensity, *J. Sci. Res. Inst.*, Tokyo, **44**, 121–137, 1950.

JACKLYN, R. M., AND A. G. FENTON, Changes in the high-latitude east-west asymmetry of cosmic rays, *Phys. Rev.*, **106**, 809–811, 1957.

LANGE, I., AND S. E. FORBUSH, Cosmic-ray results from Huancayo Observatory, Peru, June, 1936-December, 1946, *Car. Inst. Wash. Pub. 175*, **14**, 1948.

LÜST, R., Impact zones for solar cosmic-ray particles, *Phys. Rev.*, **105**, 1827–1839, 1957.

MEYER, P., AND J. A. SIMPSON, Changes in amplitude of the cosmic-ray 27-day intensity variation with solar activity, *Phys. Rev.*, **96**, 1085–1088, 1954.

MEYER, P., E. PARKER, AND J. A. SIMPSON, Solar cosmic rays of February, 1956, and their propagation through interplanetary space, *Phys. Rev.*, **104**, 768–783, 1956.

MORRISON, P., S. OLBERT, AND B. ROSSI, Origin of cosmic rays, *Phys. Rev.*, **94**, 440–453, 1954.

OLBERT, S., Atmospheric effects on cosmic-ray intensity near sea level, *Phys. Rev.*, **92**, 454–461, 1953.

PARKER, E. N., Acceleration of cosmic rays in solar flares, *Phys. Rev.*, **107**, 830–836, 1957.

SEKIDO, Y., S. YOSHIDA, AND Y. KAMIYA, Search for point source of cosmic rays, *Nature*, **177**, 35–36, 1956.

TREIMAN, S. B., Effect of equatorial ring current on cosmic-ray intensity, *Phys. Rev.*, **89**, 130–133, 1953.

The Brace Laboratory of Physics, University of Nebraska, Lincoln, Nebraska

High Altitude Cosmic-Ray Measurements during the International Geophysical Year

E. P. Ney and J. R. Winckler

Introduction—In 1947 plastic balloons became available which were capable of carrying equipment to altitudes in the range of 100,000 ft. The capability of these balloons was such that loads of the order of 50 lb could be elevated to high altitude. Because of measurements which had been made deeper in the atmosphere, it was known that only 10 to 20 pct of primary cosmic rays would be altered by nuclear interactions in the air above equipment which was flown at 100,000 ft. For this reason, it became evident that equipment to observe cosmic rays flown at such high altitudes would indeed measure primary cosmic rays with very little secondary contamination. This was in great contrast to the situation at lower altitudes, for example, at sea level, where only one out of 100,000 particles could be expected to represent primary cosmic rays. Actually, most of the sea-level particles are μ-mesons which, because of their finite lifetime, could not travel appreciable distances in space and must, therefore, be produced in the atmosphere. The initial high-altitude experiments were carried out with cloud chambers and photographic emulsions as well as with counters. During the past decade the major part of research on primary cosmic rays in the United States has been supported by the Office of Naval Research through the development of balloon facilities and grants for the scientific investigations at many universities.

For an exploratory study, both the cloud chamber and the photographic emulsions have a distinct advantage, in that they allow one to observe visually the effects of the passage of charged particles through matter. The cloud chamber gives this information through the formation of water droplets, whereas the nuclear emulsion shows visually the track of the particle by the formation of developed grains. The number of grains in a photographic emulsion along the path of a particle gives the measure of the ionization of that particle. By measuring the density of the ionization, and one other parameter, such as the magnetic curvature, the range, or the multiple scattering of the particles in the electric field of the nuclei of the material through which the particle passes, it is possible to determine both the identity of the particle and its energy. One of the interesting results of these early experiments was the discovery by the University of Minnesota and the University of Rochester groups that primary cosmic rays consisted of the nuclei of many of the elements in the periodic table in addition to the protons which had previously been supposed to constitute a majority, if not all, of primary cosmic rays. The early experiments showed as well that in the range of energies represented by cosmic rays, electrons constitute a very small fraction of the incoming high energy particles. It was clear then that primary cosmic rays represent a sample of some portion of the universe and for this reason they have become an interesting tool for astrophysical work. In the years that have passed since the discovery of cosmic rays, considerable effort has been expended in the attempt to determine their exact composition and the energy spectrum of the individual components. Much of this work was carried out by studying cosmic rays at various latitudes and assuming that the Earth, as a magnet, could be counted on to separate the particles into energy groups much as the well-known mass spectrometer does in atomic physics. It was further assumed that the field of the Earth that affects primary cosmic rays could be inferred from the Earth field measurements obtained by magneticians. The orbits and cutoff energies for cosmic rays were worked out by Störmer, Lamaître, and Vallarta for the case of a simple dipole magnetic field.

A note of the relative abundances of elements in cosmic rays is perhaps of interest. The most abundant element is hydrogen, which is approximately five times as abundant as helium. The principal uncertainty in the ratio of hydrogen to helium in cosmic rays comes from uncertainty in the knowledge of the number of incident primary cosmic-ray protons, which can easily be confused with other singly charged particles which originate in the Earth's atmosphere or just outside of it. Beyond helium, the

elements lithium, beryllium, boron, carbon, nitrogen, and oxygen are approximately in equal abundance. This is in great contrast to astronomical abundances in which lithium, beryllium, and boron are known to be almost nonexistent. It is currently believed that the high abundance of lithium, beryllium, and boron represents an effect caused by the passage of cosmic rays through space. The other elements in the periodic table up to iron appear in cosmic rays, with iron very abundant as it is in cosmic abundance. No cosmic-ray nucleus heavier than iron has been found to date and it is believed that less than one in a thousand cosmic rays have an atomic number greater than 26 or 28, that is, iron or nickel. There is approximately one iron nucleus for every thousand primary protons. In short, the abundance of cosmic rays is very similar to that inferred for an average cosmic abundance from astrophysicists, with the distinguishing feature that the iron to hydrogen ratio is perhaps higher in cosmic rays than it would be expected to be.

Recent studies of the primary cosmic-ray helium—An advantage of the heavy elements in studying cosmic rays is that they can be rather positively identified and not confused with the albedo particles in the atmosphere which make difficult the measurement of the primary hydrogen. Although the intensity of cosmic radiation at the top of the atmosphere is approximately 60 times greater than at sea level, the number of particles is still relatively small. Approximately one primary cosmic ray passes through each square centimeter at the top of the atmosphere per second at high latitude. This means that in studying some property of cosmic rays, it is desirable to choose as abundant a component as possible. Naturally, primary helium satisfies this requirement well and helium is now the most accurately measured component of primary cosmic rays. It has been with primary helium nuclei that the first study of the energy spectrum of cosmic rays has been carried out down to very low energies, without relying on geomagnetic theory.

This alpha-particle energy spectrum at very high latitudes shows the extremely interesting property that the differential spectrum, that is, the spectrum of the number of particles per unit area per unit time, per unit energy interval, is a maximum at about 300 million electron volts per nucleon, and the relative number of alpha particles at either lower or higher energies drops off. These data are presented in Figures 1, 2, and 3. Although the knee in the latitude curve led people to suspect some kind of cutoff for low-energy particles, it was quite unexpected to discover that instead of a sharp cutoff there existed a rather broad maximum in the differential energy spectrum. Whether this maximum represents an effect caused by the transmission of cosmic rays through the interplanetary medium, or whether it exists because of the acceleration mechanism is not at present known. It is probable, however, that low-energy cosmic rays will be the ones, if any, affected by solar activity. Exact knowledge of the form of the alpha-particle energy spectrum is a starting point for comparison of the alpha particles during a solar minimum and a solar maximum (Fig. 4). The experiment in which the energy spectrum was determined was carried out at Saskatoon, Canada, at a time when the Sun was at its lowest ebb of activity, in 1954. Once the energy spectrum is known at high latitude, it is possible to determine the geomagnetic effects, that is, the energy at which the Earth cuts off cosmic rays at a given latitude, by carrying out the Saskatoon-type experiment at lower and lower

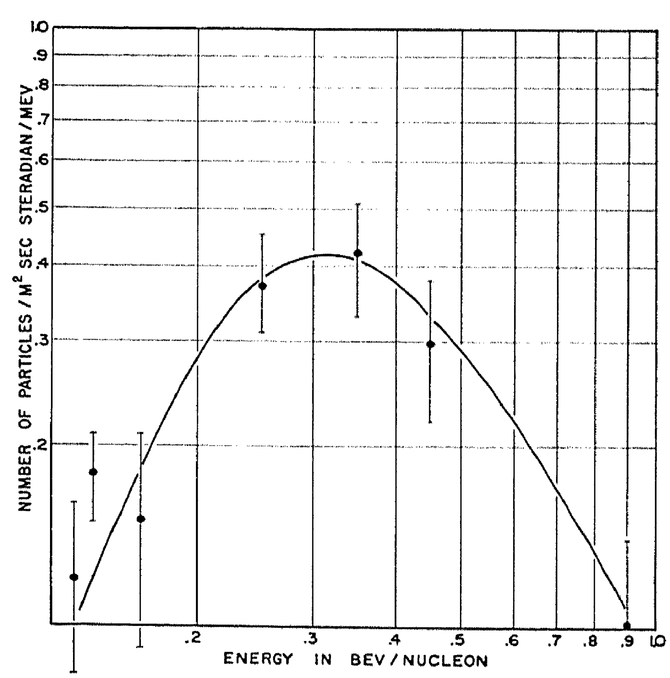

Fig. 1 — The energy distribution of primary helium incident on the Earth at Saskatoon, Canada, June 18, 1954, at solar minimum; the spectrum has a maximum at an energy of 300 million electron volts per nucleon of helium and falls away rapidly, especially on the lower energy side of the maximum

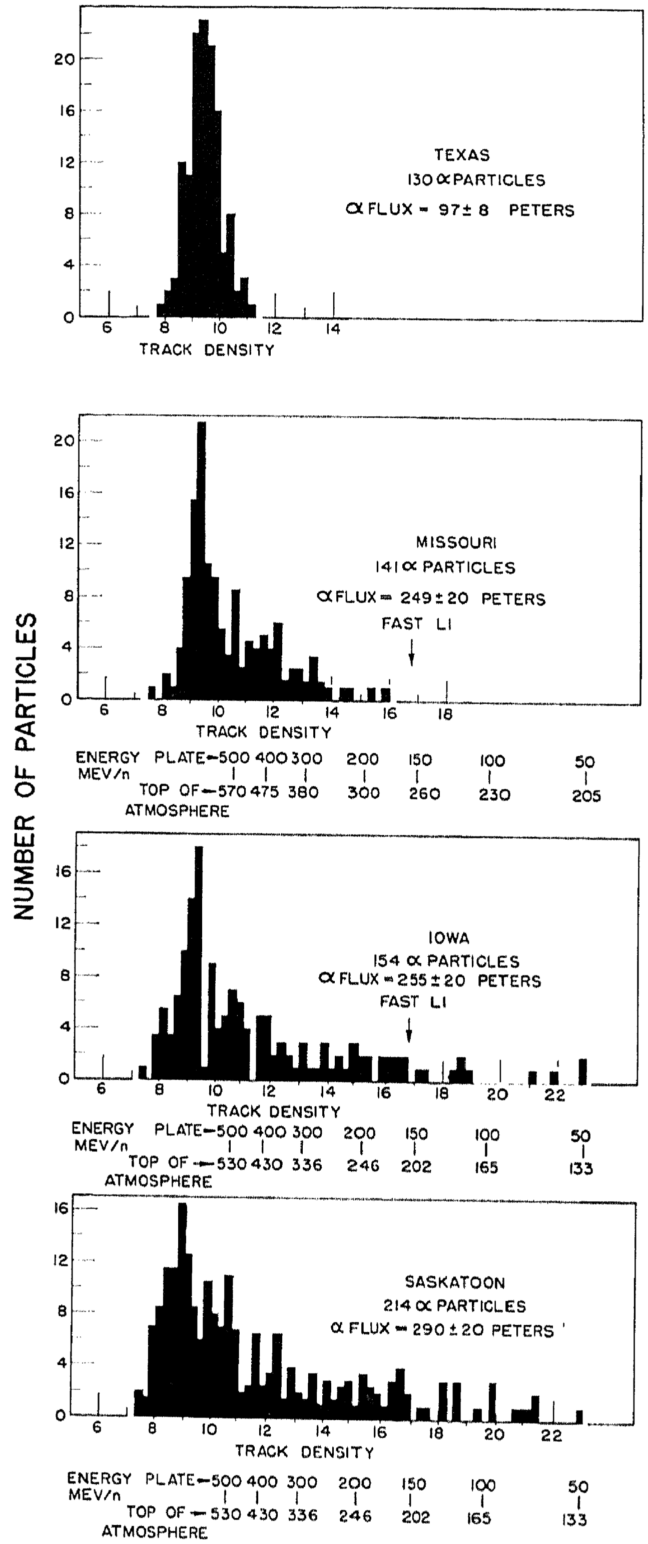

FIG. 2 — Primary helium measured at Texas, Missouri, Iowa, and Saskatoon, Canada; the number of particles in each increment of track density in the nuclear emulsion is plotted; the energy of the α particles corresponding to the observed density of ionization is indicated below; the lowest energy arriving at Missouri is about 300 mev; according to surface magnetic survey analysis, the cutoff should have occurred at Minneapolis four degrees of latitude farther north

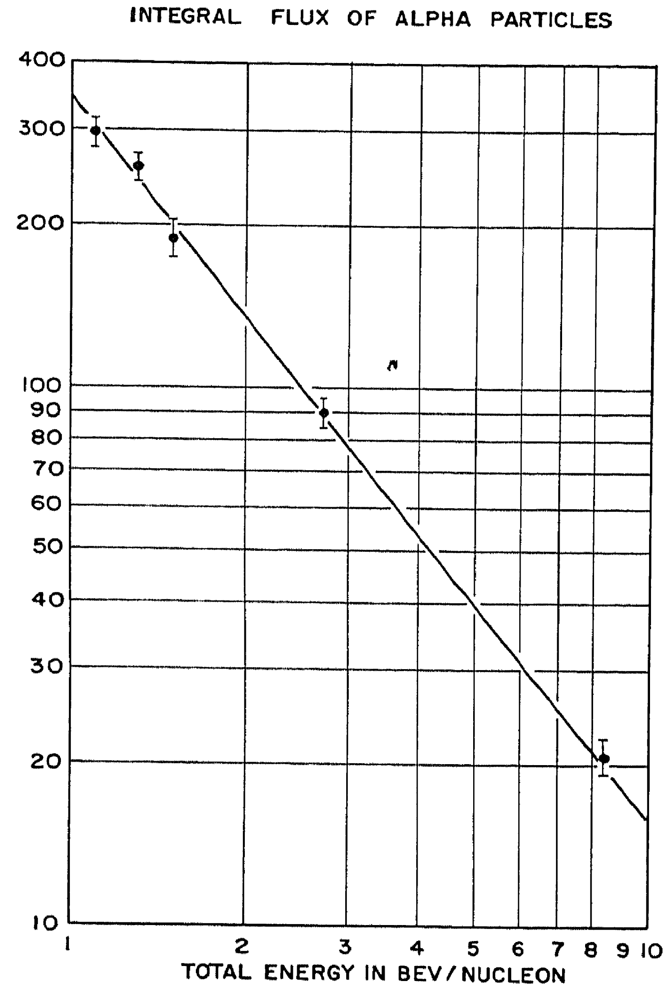

FIG. 3 — The total flux expressed in particles/m^2 sec unit solid angle of primary helium having energies greater than the values plotted below (integral spectrum) over most of the region of energy affected by the Earth's magnetic field

latitudes. This was carried out at Minneapolis, Minnesota; Waukon, Iowa; Kirksville, Missouri; and San Angelo, Texas. It was found that the energy spectra in Minneapolis and in northern Iowa were identical with that at Saskatoon and that the Earth's magnetic field did not cut off particles until the latitude of northern Missouri was reached. This allowed one to determine the effective cutoff produced by the Earth's field and led to the startling conclusion that the effective latitudes which one must use to compute cosmic-ray cutoff energies in the United States are four degrees higher than one would expect from the geomagnetic coordinates. The general features of the Earth's magnetic field in determining cutoff energies are shown in the set of curves of Figure 2 which show the relative number of particles of various energies observed at the latitudes previously referred to. In Texas,

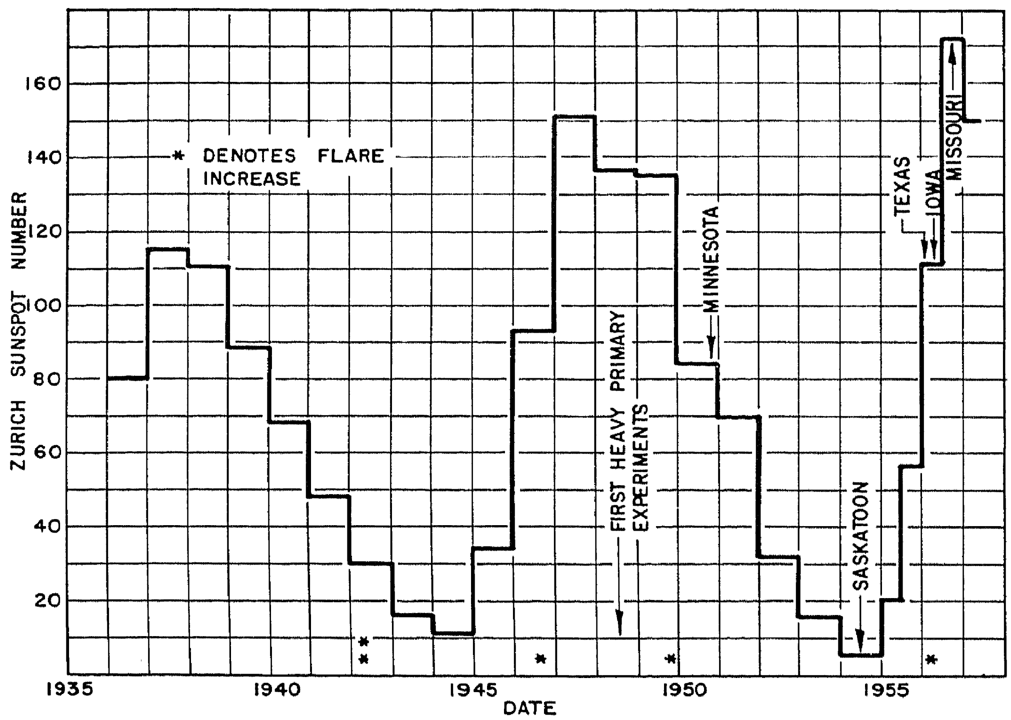

FIG. 4 — The Zurich sunspot numbers showing the growth and decay over the two most recent solar cycles; large cosmic-ray increases occurred at times indicated by asterisk accompanying solar flares

because of the high cutoff energies, essentially all the particles are at very high energy.

One might summarize the knowledge obtained concerning the alpha particles in the following way. We now know their differential energy spectrum at low energy during the time when the Sun has minimum activity. We also know the effect of the Earth's magnetic field in imposing a cutoff on the primary cosmic rays, that is, we know what latitudes have been associated in the past with definite vertical cutoff energies.

The primary cosmic-ray hydrogen—Hydrogen is the most abundant component of the primaries and constitutes about 85 pct of the total primary particles. This result is based on somewhat indirect evidence because of the experimental difficulties of identifying primary protons. For example, photographic emulsions from the moment of manufacture accumulate a background of tracks from fast sea-level cosmic rays which are indistinguishable from primary singly charged particles. This background exposure is further increased during the ascending portion of a balloon flight. At high altitude both emulsions and counters record secondary singly charged particles generated in the atmosphere and others which appear to come from outside the Earth but are really 'albedo' particles spiralling in the magnetic field just above the atmosphere and are also of secondary origin. These secondary and background particles make it extremely difficult to extract directly an energy spectrum of the primary protons in the manner used for helium, even in the low-energy region where this is in principle possible. One therefore has to use the best knowledge of geomagnetic theory to determine the cutoff energies at each latitude, and to measure the singly charged particle flux at very high altitudes over a range of latitudes from the pole to the equator. Such measurements made with Geiger counter coincidence trains, or 'telescopes,' are shown in Figure 5 over a range of latitudes. These simple detectors include many of the undesirable secondary effects discussed above. The effect of lower-energy secondaries as well as fast particles coming back up from the atmosphere below may be measured and eliminated by using a device called a Cerenkov counter which consists of a high sensitivity photomultiplier tube connected to a block of lucite. Because of the index of refraction, a charged particle may travel in the lucite faster than the speed of light waves, and create an electromagnetic bow wave which travels with the particle like the shock wave attached to a bullet. The signal reaches the phototube only if the particle is moving towards the tube through the lucite block. The primary-particle intensities corrected

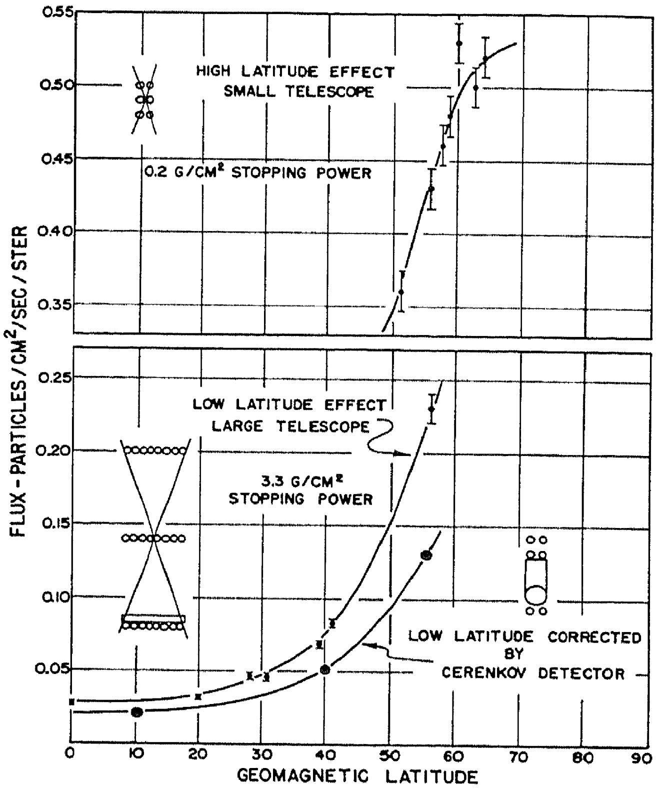

FIG. 5 — The total flux of particles at the top of the atmosphere measured with Geiger-counter telescopes (upper two curves) over two regions of latitude; the lower curve is the result when atmospheric secondary particles are eliminated by use of a Čerenkov detector

by this device are shown in the lowest curve of Figure 5. In Figure 6 these measurements are translated into the distribution of particle magnetic rigidities for total primaries, which includes protons and heavy nuclei. The magnetic-rigidity spectrum is used since for all particles the Earth-field magnetic-rigidity cutoff is the same at any particular point on the Earth's surface. This spectrum shows a gradual flattening towards lower rigidities. The curve shifted to the left is based on geomagnetic cutoff values derived from direct alpha-particle measurements as discussed under *Recent studies of the primary cosmic-ray helium*. These curves of Figure 6 are representative of the period of minimum solar activity in 1955 (Fig. 4).

Primary intensity variations—One very fascinating topic is how the primary cosmic rays change during solar disturbances, and intensive study will be made of this during the International Geophysical Year. In the past, measurements carried out over a period of years with ionization chambers on sounding balloons near the geomagnetic pole by H. V. Neher of California Institute of Technology show that when the solar activity, indicated by sunspot numbers, reaches a maximum on the 11-year cycle, the cosmic-ray intensity decreases. This may be due to clouds of magnetic material thrown into space by the Sun, or possibly the setting up of a ring current around the Earth one or more Earth radii above the surface.

In addition to these intensity decreases, sporadic increases probably caused by direct production of cosmic rays by the Sun during large solar flares are observed. The largest such on record occurred on February 23, 1956, and was recorded world-wide. A balloon sounding made during this flare at the University of Minnesota is shown in Figure 7. The particle flux at the

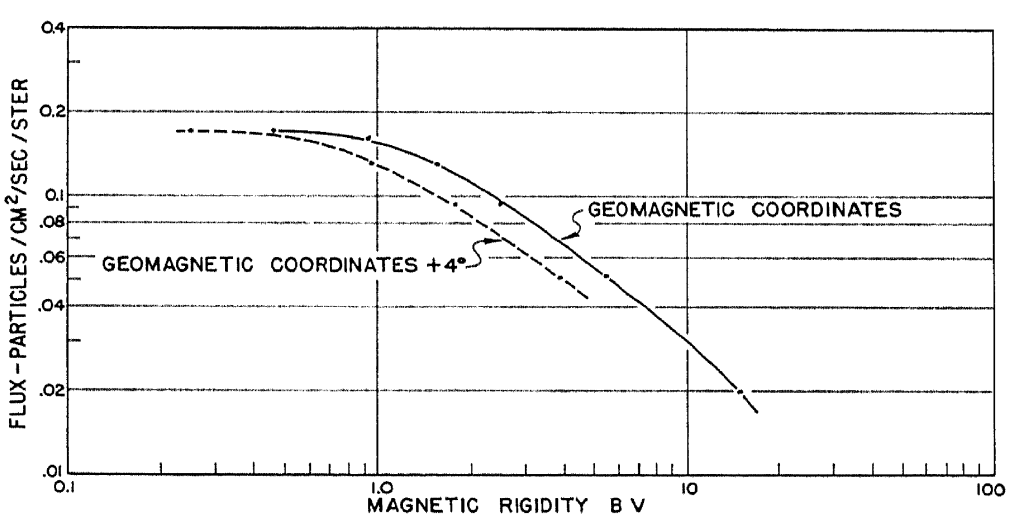

FIG. 6 — The total number of cosmic-ray primaries having rigidities greater than the values plotted below measured in billion volts; if the geomagnetic coordinates are shifted north by four degrees of latitude as suggested by α-particle results, the displaced curve results

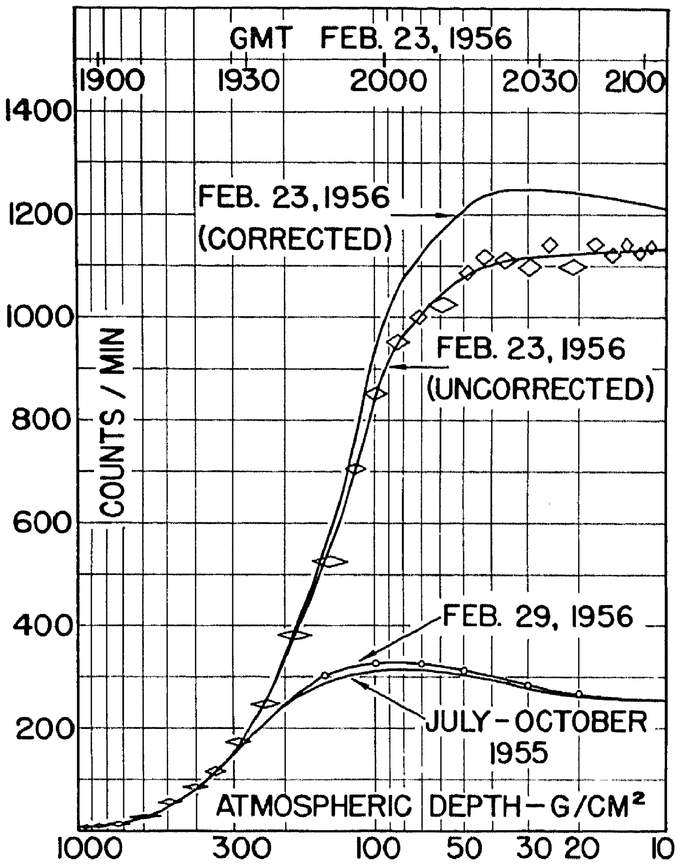

FIG. 7 — Record of the counting rate of a Geiger counter coincidence train sent from sea level (1000 g/cm^2) to 100,000 ft (10 g/cm^2) towards the end of the great cosmic-ray increase of February 23, 1956; normal soundings are shown in the lower curves; these cosmic rays were accelerated near or on the Sun and probably diffused to the Earth by greatly extended paths in magnetic fields in the solar system

top of the atmosphere is five times normal 17 hours after the start of the flare. It is estimated that the cosmic-ray maximum intensity reaching the Earth was one thousand times normal during this flare at Minnesota. Only five such large flares have occurred in the last two solar cycles. Another example of a smaller, short increase observed during balloon flights at Minneapolis and simultaneously in northern Manitoba is shown in Figure 8. Continued observations with this apparatus (a small Geiger counter coincidence train flown on sounding balloons) show that the primary cosmic-ray intensity at Minnesota in May of 1957 has dropped to nearly half of the value measured during 1956 with the same apparatus. Typical soundings are illustrated in Figure 9. The points represent counts per minute obtained from cosmic-ray particles at various heights up to 100,000 ft. At that altitude the largest relative effect appears.

Balloon program for the International Geophysical Year at Minnesota—The IGY program at Minnesota was conceived with the idea of monitoring the primary cosmic rays at high altitude and at one location. It was decided to use constant-level plastic balloons floating at about 100,000 ft and remaining aloft for about 24 hours. Fifty to 70 flights distributed over the IGY period are planned. The apparatus was chosen to reveal short- and long-term primary intensity changes, and to give as much information as possible about what components of the primary beam wave were changing. The components of the system are (Fig. 10 and 11):

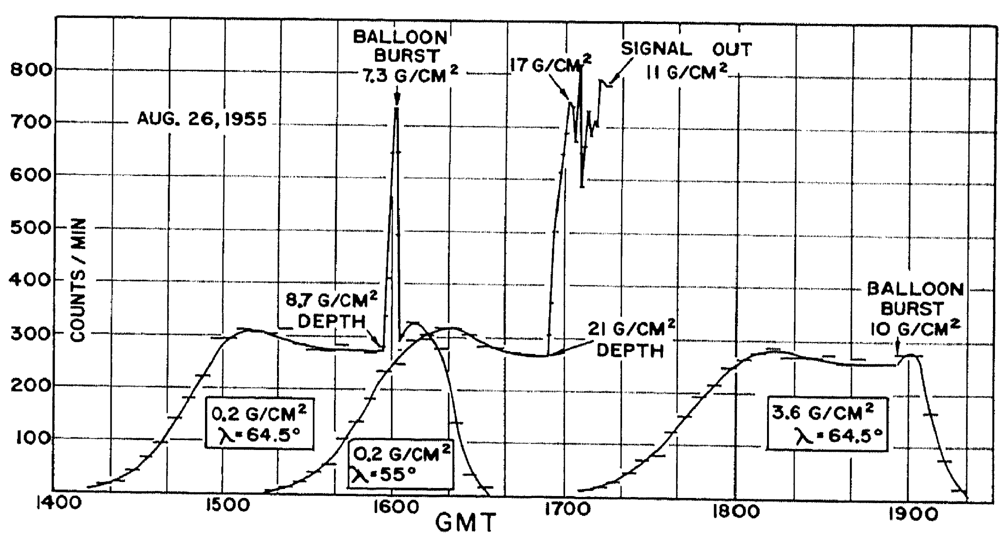

FIG. 8 — Record of two increases observed one hour apart at Minneapolis (geomag. lat., 55°) and at Flin-Flon, Manitoba (geomag. lat., 64.5°) August 26, 1955

(a) A plastic balloon of modern design, made of very lightweight polyethylene or the newer ¼ mil mylar plastic, of volume 60,000 to 150,000 cu ft and weighing 50 lb or less. (b) A single Geiger counter unit with scaling-down circuit. The counter responds equally to particles from all directions, and gives the total omnidirectional particle flux (Fig. 12). (c) A spherical integrating ionization chamber (Fig. 13). This records the total ionic charge produced by cosmic rays per second, and therefore the total energy influx on the Earth's atmosphere. Indirect information about relative primary ionization and fluctuations in heavy nuclei may also be obtained. (d) An emulsion package which is carried to the ceiling in a horizontal position, and when the balloon has reached its ceiling altitude, is allowed to acquire a new position in which the plate stack

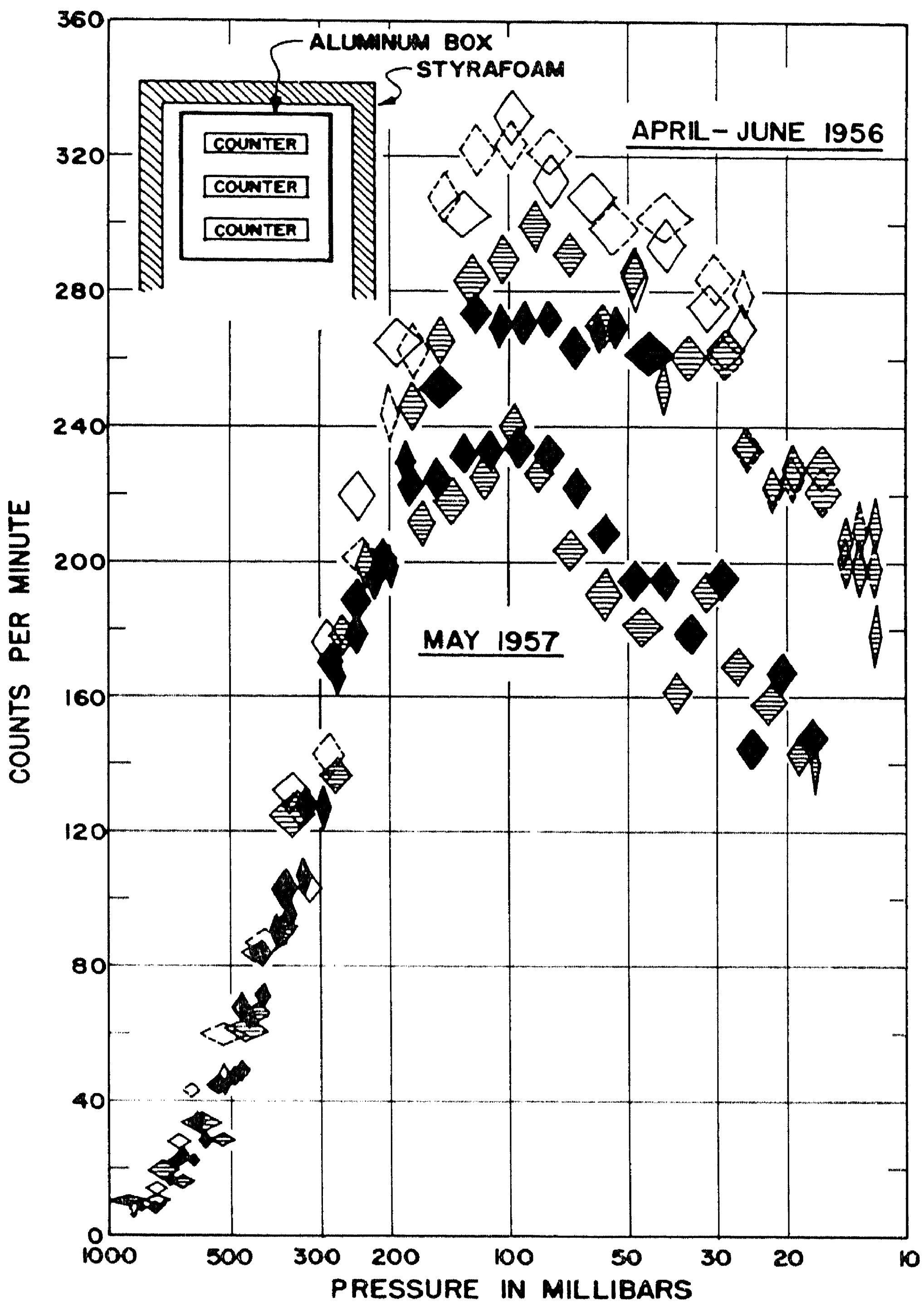

FIG. 9 — Record of the depression of cosmic-ray intensities at high altitude at Minneapolis in May 1957 (lower curves) compared to a similar period in 1956; this decrease comes at the peak of the sunspot cycle and precedes the beginning of IGY by several months

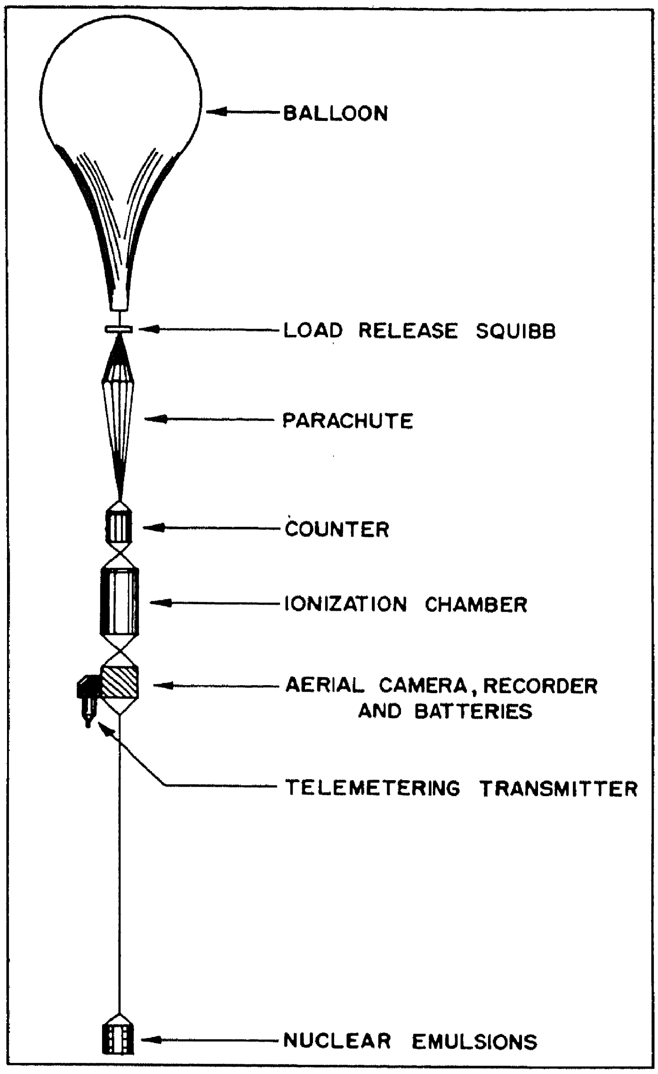

FIG. 10 — Flight train for IGY cosmic-ray monitoring; the balloons had a volume of from 58,000 to 150,000 cu ft and carry the load to 100,000-ft altitudes; after approximately 24 hours of flight, the load is released by firing the squibb electrically from the recorder package; the entire load train then drops to the ground by parachute for recovery

is in a vertical direction. By using this technique one can be sure that the alpha particles studied are those which came in under a fixed atmospheric depth. We will study the alpha-particle plates at those times when the counter or ion chamber shows that the overall intensity is abnormally high or abnormally low. Because of the rather large amount of time required to do an alpha-particle experiment, it will not be possible to examine in detail each pack of plates flown. (e) A recording and telemetering package containing a small aerial camera for mapping the balloon trajectory by down photos. Figure 14 is a typical balloon trajectory constructed from the down photos, and illustrates the great accuracy of this method of tracking. This camera also records the counter, ion chamber, and pressure instruments, and terminates the flight after a predetermined length of film has run through. The load then descends by parachute. The telemetering uses a modified Weather Bureau radiosonde unit, and transmits the counter, ion-chamber, and pressure records. The radiosonde receiving and recording system automatically tracks the flight and records the angular position of the balloon while it is within radio range.

Preliminary work began about one year ago, and in the course of developing the equipment occasional test flights, flown as hitch-hike loads on other balloons, were made. In the course of this preliminary work with the IGY ion chambers, counters and plates, the large decreases in primary intensity noticed with the other cosmic-ray detectors mentioned earlier was measured.

Figure 15 shows the results of two IGY-type measurements made in September 1956 and April 1957. The total particle flux and total ionization have decreased by $\frac{1}{3}$ in that period, marking the arrival of maximum solar activity. These curves (Fig. 15) show only a portion of the data obtainable from one such flight. The nuclear emulsions flown require a longer time to evaluate, so that relative changes in the light and heavy components of the cosmic-ray primaries have not yet been determined. It will indeed be extremely interesting to determine whether or not the Sun has a direct or modulating effect on the alpha-particle component of primary cosmic rays. This is a component which can be definitely associated with cosmic rays themselves, and about which we now have enough information so that studies during the IGY will indicate changes from the state of affairs which existed at the solar minimum.

The balloon launchings on this Minnesota program will be timed when necessary to coincide with other high altitude cosmic-ray measurements in balloons and rockets. Launchings may be made swiftly following indication on ground-level monitors that a flare increase has occurred. Such a monitor with a warning system is now available at the University of Minnesota cosmic-ray laboratory. In the event of a large flare, we will fly a number of balloon flights of the standard IGY type, in the hope of measuring the abundance of the heavy elements during such occasions. A very important result which would be obtained from such a measurement

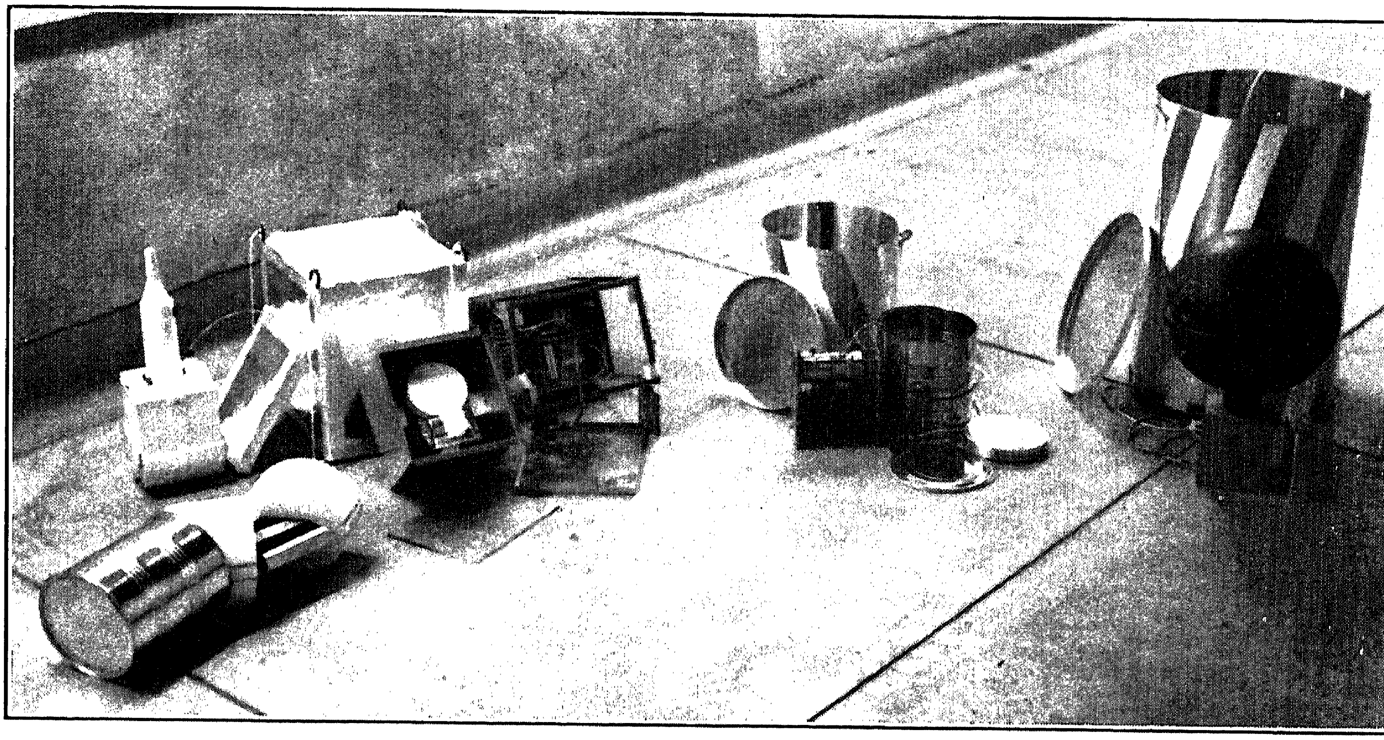

FIG. 11 — Dissembled view of load equipment; left front, emulsion package and can; left rear, telemetering transmitter, battery box, camera, and pressure recorder; right, transistorized single counter and spherical ion chamber

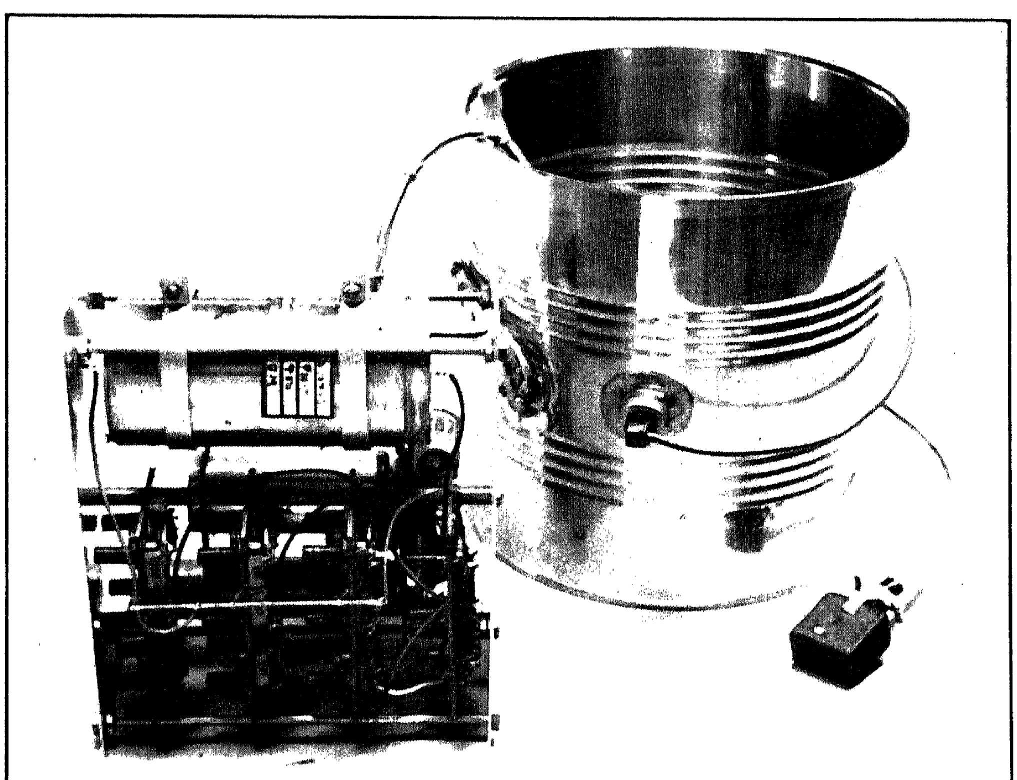

FIG. 12 — Geiger counter with transistorized scale of 512 and 1000V power supply; unit is pressurized in the one-gallon can

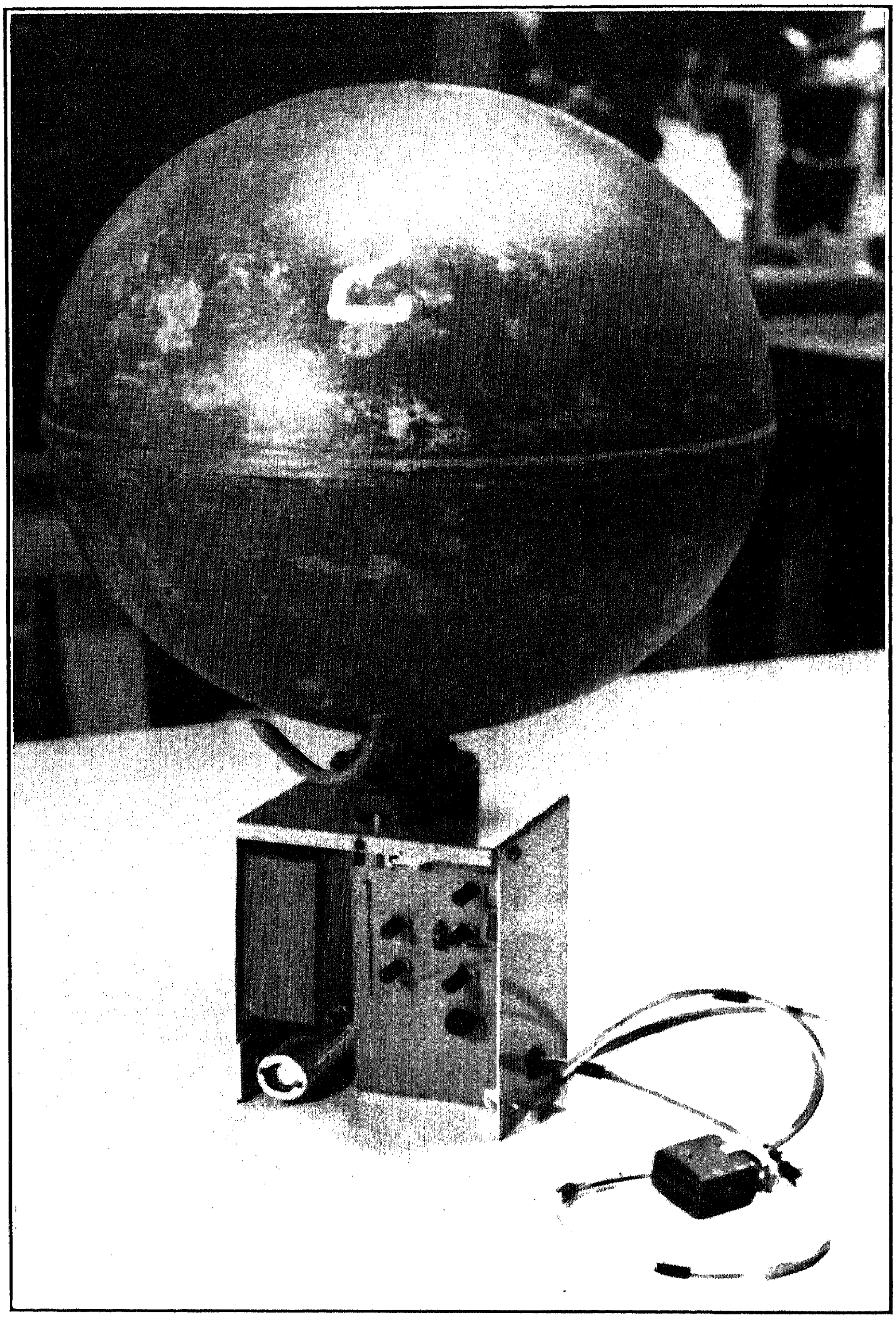

FIG. 13 — Spherical integrating ion chamber with battery and transistorized circuit for recording and telemetering

would be the knowledge of composition of elements on the Sun, in particular one might be able to measure the hydrogen to helium ratio on the Sun, as well as the carbon, nitrogen, and oxygen abundances, and allow us to determine something about the type of nuclear energy furnace which the Sun is. Since the large solar flares are quite rare, one must however be willing to be satisfied with the possibility of studying the less spectacular events such as the present general low intensity described above.

Further balloon development during the IGY —There is at the University of Minnesota a joint program of the Army and Office of Naval Research for the study of balloon physics and atmospheric physics. One of the consequences of this work which very nicely complements cosmic-ray and IGY research has been the development

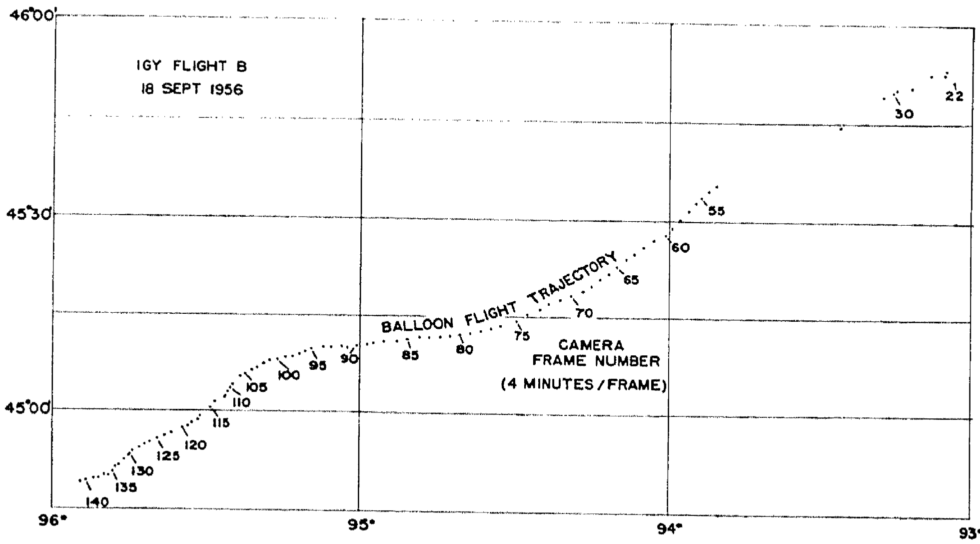

FIG. 14 — A typical flight trajectory in summertime; the balloon was launched from north central Minnesota and drifted southwestward; the load dropped in western Minnesota; the camera frame numbers are given, with one exposure taken every four minutes; the balloon altitude on this trajectory was 115,000 ft

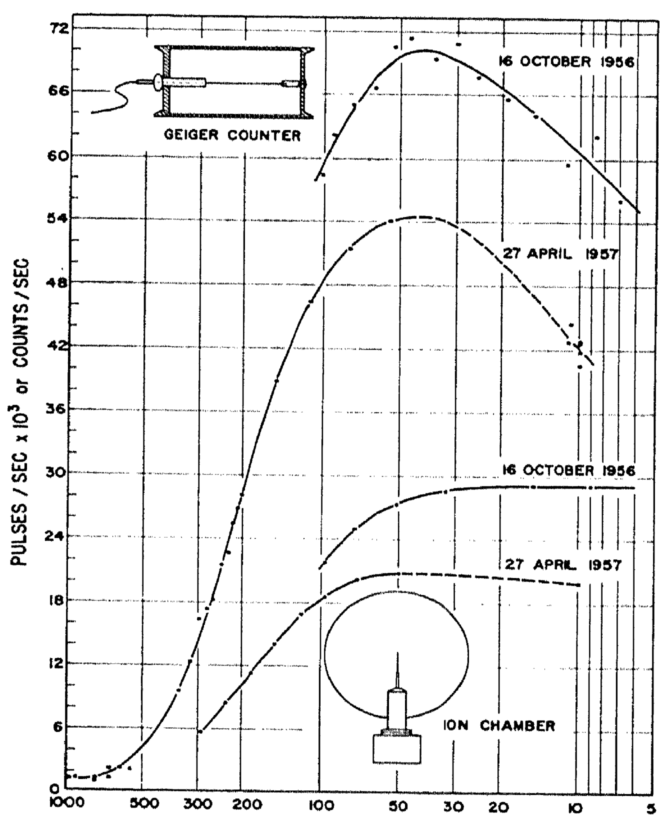

FIG. 15 — Change in primary cosmic-ray intensity recorded with preliminary IGY measurements at high altitude; the total omni-directional particle flux and the total ionization at high altitude have dropped 31 pct between the dates shown; the decrease coincides with time of maximum sunspot numbers for the present cycle

of various unique balloon capabilities. Because of its probable use during the IGY and for IGY flights, we mention here a unique and interesting balloon design which was the result of this atmospheric physics work. The balloon is called a tetroon, and has roughly the shape of a tetrahedron. It is constructed of ¼ mil mylar plastic and has performance capabilities greatly in excess of the skyhook balloons which were constructed of polyethylene one mil thick. Because of the smaller weight per unit area of the plastic, it is of course important to design the equipment which is flown to a minimum weight. To give an example of the possible performance acquired with mylar balloons, one may quote results of a flight carried on in the atmospheric physics program in which a 160-ft gore length mylar tetroon was flown to an altitude of 145,000 ft or a residual pressure of two millibars. The balloon for this flight carried an instrumentation load of 25 lb, had a volume of 1,000,000 cu ft and a weight of only 100 lb. The ¼ mil mylar tetroon, when compared with a similar shape and equal size one mil polyethylene balloon, will fly at an altitude 32,000 ft higher than the polyethylene balloon, or will carry a small load to a residual pressure which is three times less than that which would be reached with the polyethylene vehicle. We hope it will be possible for us to use a large number of balloons of this type in our IGY series of flights.

Physics Department, University of Minnesota, Minneapolis, Minnesota

Visual Observation of the Aurora

C. W. Gartlein

Introduction—The aurora has been observed visually for hundreds of years, but its scale was not appreciated until the last century. Catalogues of the dates of occurrence showed that it was widespread on some dates and it came to be regarded as a polar-zone phenomenon. The work of *Loomis* [1860], and especially that of *Fritz* [1873], showed that there was a zone of maximum frequency of appearance. This zone was found to be centered about the axis of the magnetic dipole field of the Earth. It was then clear that the aurora was caused by charged particles coming into the Earth's atmosphere. The work of the earlier investigators was refined by *Vestine* [1944]. While the zonal character was always shown, the data were insufficient to give a curve of frequency of overhead occurrence. It gave only the frequency of visibility. A principal goal of the IGY is to refine this frequency curve and answer questions such as: If the aurora has moved south of the zone, has it also moved inward? Does it play a role in a given display or is it only a long-time average statistical effect?

Early work—In spite of the volumes of data, the number of careful moment-to-moment records is quite small, and the number of simultaneous records over a wide area is still smaller. One of the first organized groups covering a large area began in 1825 in New York State and continued until about 1851. The academies (high schools) of New York were required to observe the aurora as part of their meteorological observations. Comparison of reports from several stations showed that the appearance of a given display changed little from place to place. The great variability of the forms of the aurora made classification difficult, but by 1929 the usual classification contained twelve standard forms, based on the appearance and supposed meaning: glow, homogeneous arc, homogeneous band, rayed arc, rayed band, drapery, rays, corona, flames, pulsating arc, pulsating surface, and diffuse surfaces. However, the definitions were far from exact. This has plagued the setting up of the present international auroral watch. There has been difficulty with deciding what is important. As the visual observer can write down only a limited description, he can not be sure he is recording what is most important. He looks for a regular course of events in the bewildering variety and asks what the sudden changes mean.

The oldest measurements of heights was made by visually measuring elevation angles. The work of Loomis in patching together many observations from the September 1859 display gave lower heights of about 100 km and maximum tops to over 600 km. The photographic measures, principally by *Störmer* [1955], give reliable heights from about 70 to 1100 km. An important fact is that the lower edge of the aurora almost always lies at 100 to 110 km above the Earth, and the height of a given form is quite constant along its length. Certain forms, narrow faint white arcs and red arcs were at 200 to 300 km, and isolated rays often extended from a height of over 300 km to 1000 km. The height measures in Norway, Alaska, New Zealand, and New York show a close agreement, apparently quite independent of latitude variations.

The visual observations long ago showed that the aurora increased in its intensity and frequency as magnetic activity increased. The slant of the rays and the position of the corona showed the inclination of the Earth's field and its change.

Recent work—Since 1930 several observational programs have run more or less continuously. A group began in New Zealand in about 1934, and has continued. Their work is in the process of summarizing now. It has given a number of good descriptions and approximate rules of behavior. A group in England of the British Astronomical Association has been in operation since 1940, but most active since 1952.

The group in northern United States and southern Canada reporting to Cornell University began in 1938 under the sponsorship of the National Geographical Society. It later had support of the U. S. Signal Corps and the U. S. Information Agency. The group consisted of volunteer observers from amateur and professional astronomical societies and had help from certain U. S. Weather Bureau Stations. The present IGY program of the United States and Canada is an

outgrowth of this program. Many reporting methods have been tried and found wanting.

In the first scheme the observer listed the forms in order of appearance in a space for each hour of the night and specially noted times of change in the aurora. The report sheet gave a space for each night hour during one month. Many observers wrote descriptions. Transcribing the data showed the need for having the data on separate sheets for shorter time intervals, say one night. In the second manner of reporting the observer wrote descriptions in successive lines on a sheet for a given night. The sheet was ruled into columns for time, intensity, elevation, form, and remarks. This was not entirely satisfactory either, I think, because one could not outline the observing procedure well enough, and especially because relating a part of the aurora seen at one time to its earlier appearance is very cumbersome.

In 1951, Kimball and Gartlein devised a graphic form for observers from the American Association of Variable Star Observers. The report form was a series of tall rectangles set side by side. Each rectangle represented the north sky and was divided into several angular intervals. The observer entered his observation by plotting schematic representations at the proper angular elevations. Observers had no difficulty with this and it was easy for the analyst.

The IGY program—In 1955 a system of mark-sense reporting was initiated as a trial run for the IGY. The observer reported principally the appearance along his meridian. He first measured the angular height of the lower borders of the aurora by sighting with an alidade. After he made a mark along the sighting edge and labeled it with the form name. This card properly marked constituted a valid report for a specific time, but the observers were asked to transcribe these observations to a mark-sense card which could be made into a punch card automatically in the collecting office. Many observers found this difficult and we got nothing from them, but the results from the remaining group are impressive. A great virtue of this mark-sense card is that in effect it asks the observers questions, such as: Did you see a rayed arc between 20° and 32°? Was any lower border red, if so where? It offered the possibility of a kind of universal language also.

The present United States—Canadian program retains most of the advantages of the punch-card system, but in a graphic form applied to the entire sky. The sky chart is an adoption of that used for many years by Millman in a Toronto newspaper series on astronomy. The observer is asked to report what he sees on the quarter hours by sketching the auroral forms in their apparent positions in the quadrants representing the sky. The divisions in the sky at 62°, 32°, 21°, etc. indicate distances from the observers of $\frac{1}{2}$°, $1\frac{1}{2}$°, $2\frac{1}{2}$°, etc. for the lower borders of auroras at 100 km height. The observer can use words or abbreviations if he chooses. The data can be sorted easily and plotted directly on the map. The number of reporting forms has been reduced from 12 to 8 and the definitions improved. The forms are unclassified arcs, homogeneous arcs, rayed arcs, isolated rays, pulsating forms, flaming forms, glows, and spots or patches.

The Canadian and United States programs are identical and a plotting map was produced for the program by the Surveys and Mapping Branch of the Canadian government. In addition, the observers of the North American program are provided with a filter to detect aurora and an inclinometer to measure angles. The Handbook for Reporting Auroras contains detailed instructions. The observers in this program number over 200; they range from southern California to northern Maine (Fig. 1).

About 100 U. S. Weather Bureau stations and 16 in Alaska report once per hour on simple mark-sense cards. This program has been in operation since early March 1957 and there are no serious difficulties. The data from this program will form the basis for the first-run synoptic maps.

In the Antarctic the observers use the 1955 mark-sense program, but have means to adopt the graphic system at any time. A program of observation was run at Little America and McMurdo Sound by aerologists of DEEP FREEZE I. Weather Bureau mark-sense cards were used. The methods of the visual program can be used to read data from the all-sky camera films. An IBM punch card has been designed for use in the North American program. Electric punching or mark sensing can be used as seems best when we get into the detailed work.

The visual program should produce more important results than the older programs have

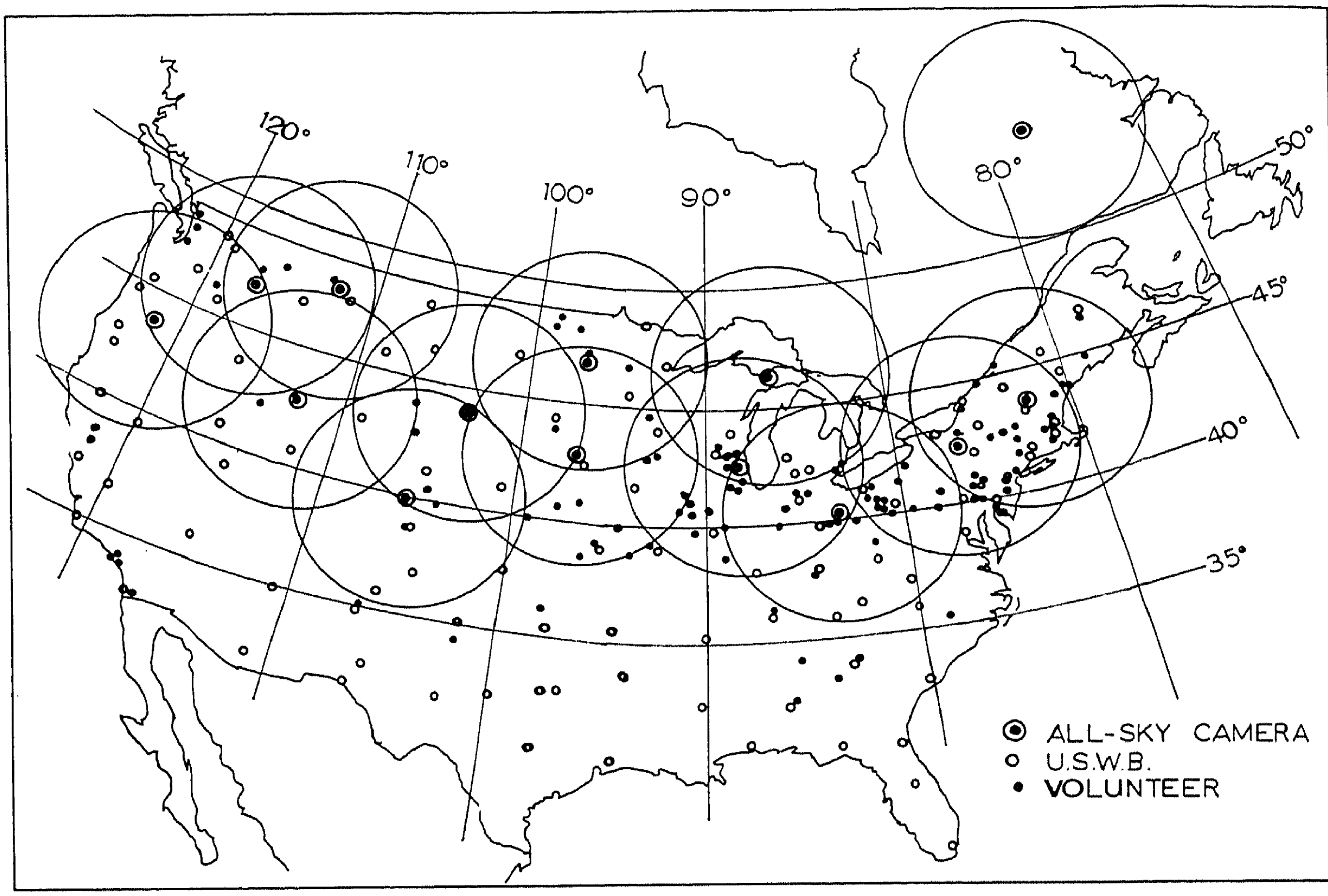

FIG. 1 — Map of IGY Auroral Coverage—United States

done. They have shown that (1) the brightness of lower latitude auroras increases with increasing K number, (2) auroras go farther south as K number increases, (3) the aurora is farthest south near midnight, (4) ray forms go about 2° of latitude farther south than arc forms (Fig. 2), (5) the cross section of the auroral zone can be defined and the zone moved south about 2° during the years 1955 and 1956 (Fig. 3), and (6) visual observations can show the sign of the incoming charged particles.

Though this last result is so new and all the

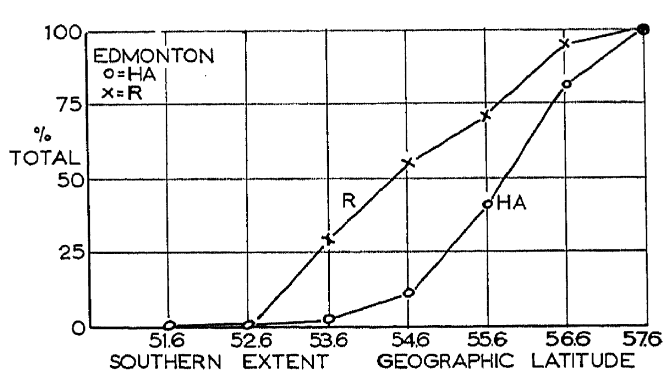

FIG. 2 — Frequency of occurrence of ray forms and arc forms as a function of geographic latitude

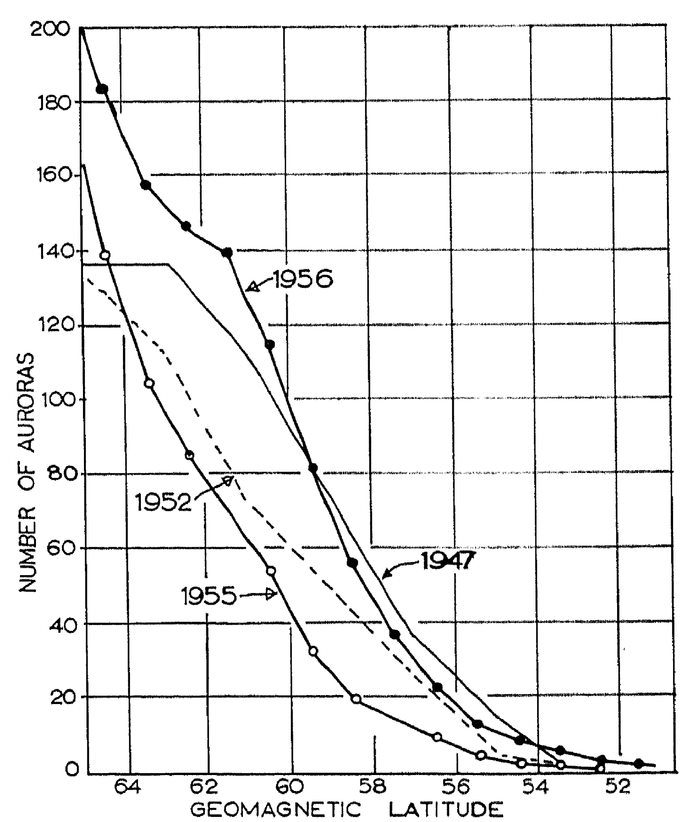

FIG. 3 — The number of auroras which occur at and south of a given geomagnetic latitude

applications have not been made, it appears to be a great aid to our understanding, and these results are presented so they can be used and checked by any observer.

Theoretical considerations—We must now consider the meaning of these auroral forms. To do this we will consider laboratory work on a subject far from geophysical research, a study of how electron beams behave in a laboratory vacuum tube. Workers on high frequency radio transmitting tubes, apparently traveling wave tubes, have known that the tubes failed to work when the beam became too intense. Various workers had this difficulty, but the nicest study is that by *Kyhl* and *Webster* [1956] of the General Electric Laboratory. In their tube a beam of electrons is emitted into an electric-field free space, but along a magnetic field. The beam usually starts down the tube as emission from a narrow circular slit, though flat beams have been used. They have used pulse techniques to study the beam. They found that the beam maintains its circular cross section as it travels when the charge density is small. But if it travels far enough it will gradually fly apart, not in a helter-skelter fashion but in spiral and curve formations. If the beam intensity is raised, the same curves result in a shorter travel distance. They studied the mathematical equations of this beam and published the report cited.

H. F. Webster and G. Branch, other workers in this field, discussed this with Gartlein and Sprague at Cornell in January 1956 as they suspected these curves might occur in the aurora. We examined still pictures and movies of the aurora and at once saw the relation to the aurora. The sign of charge is reversed. A detailed application of this experiment to the aurora must be made. We have been able to spend only four hours conferring on this and not many hours in thinking about it.

Since we have only a short time to discuss this, let us consider a beam of protons moving downward along the lines of magnetic force (Fig. 4). The beam is assumed focused into a flat sheet outside the Earth's atmosphere. This beam is constrained by the magnetic field so protons expanding outward to north will curve toward west, while those moving out toward south will bend toward east. If the beam is wide in north-south, then there is a general drift to west on the north side and to east on the south side.

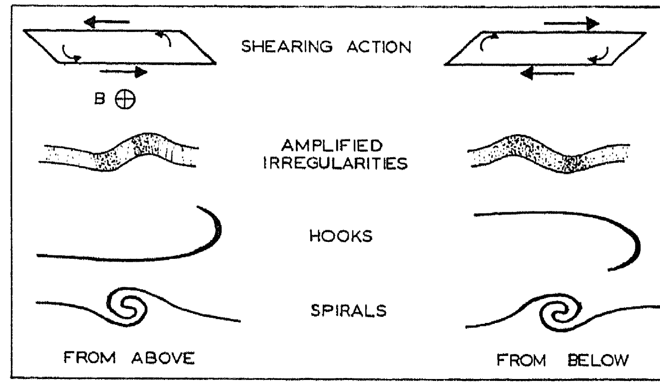

FIG. 4 — Distortion of beams of protons moving in a magnetic field

Thus the ends of the beam are slanted. Every one of these seen in the aurora photographs is slanted right to left as seen in the north.

If the beam is not quite uniform, or it has traveled farther, the more intense parts will begin to curve into an S shape figure as we look along the beam. If the intensity is raised, these curves go into spirals. Pictures of these spirals have been taken at Ithaca and Saskatchewan. We must remember that these changes are going on as the beam moves in space, and the final light of the aurora reveals this cross section of the beam.

This breaking of the sheet into narrow rays is an intensity effect, or an effect of greater travel distance. A sheet of charge is not a stable configuration. It does not depend solely on the absolute charge density. The same pattern occurs in a weak beam after more extended travel. If there are only short pieces of beam, the east end will bend north.

Some general remarks characterize these phenomena: (a) wide beams will not bend in sharp curves; (b) in a given formation the brightest parts will become most curved; (c) the breakup into rays will occur at the time of maximum brightness or before; (d) broad beams may not break into rays; (e) the narrower the beam or the higher the brightness, the more sure the breakup; (b) when short sections of beams are left after breakup, they will rotate clockwise as we look up in the sky.

The calculations, considering the beam as protons, give curves of a size found in the aurora. We therefore conclude, on the basis of the theory and the photographs examined, that the aurora, from the time of arc formations until well after the time of ray formation, is the expected effect of a sheet of protons moving

along a magnetic field. This theory requires that the curves in the southern hemisphere be reversed. There a spiral would appear twisted in the anticlockwise direction. The only solid evidence we have on this is that characteristic pictures drawn in New Zealand are reversed from ours.

At minimum, this gives another direct evidence of the entry of charged particles into a magnetic field shown by the curved forms. This theory also may enable us to detect the cases where electrons play an important role, as possibly in flames or pulsating aurora. The theory suggests that broadening of the hydrogen lines, the spreading velocity, and the size of the formations may indicate the distance to the focusing region. It also says that if a rocket is to enter an aurora form we should aim at a wide arc, which will bend little. The narrow ones will bend and soon fly apart.

Photographs which show the effects as clearly as the laboratory experiments are unusual because the focusing may not be good and may introduce perturbations. In addition the motions involved blur photographs in a second or two.

Those of us involved now feel we understand much of what we see. It seems to explain so much in such a straightforward fashion. It also certainly points toward the existence of a focusing region or a forbidden zone envelope at a considerable distance from the Earth. It strongly suggests that changes of the spectrum are largely atmospheric.

References

Fritz, H., *Verzeichnis beobachteter Polarlichter,* Akademie Wien, 1873.

Kyhl, R. L., and H. F. Webster, *Instability of hollow beams,* Gen. Elec. Co., Research Information Section, Report 56-RL-1556.

Loomis, Elias, On the geographic distribution of auroras in the Northern Hemisphere, *Amer. J. Sci. Art,* ser. 2, **30**, 89–94 (map opposite p. 160), 1860.

Störmer, C., *The polar aurora,* Clarendon Press, Oxford, 1955.

Vestine, E. H., The geographic incidence of aurora and magnetic disturbance, *J. Geophys. Res.,* **49**, 77–102, 1944.

Physics Department, Cornell University, Ithaca, New York

The Night Airglow

Franklin E. Roach

Introduction—It is known that the night airglow has the following properties: (1) it is faint, usually invisible; (2) it is variable in intensity, over the sky and with time; and (3) it originates in the Earth's upper atmosphere. These qualitative statements can be made quantitative or, at least, semi-quantitative. It is my purpose in this paper to discuss some of the current research results with absolutely calibrated photometers capable not only of isolating individual airglow radiations, but also of systematically scanning the sky many times during a night.

Historical background—The airglow was discovered by astronomers who found a persistent radiation at a wave length of 5577 Angstroms on long exposure spectrograms. They noted that the radiation becomes systematically brighter from the zenith toward the horizon, a fact which can be readily understood on the basis of an atmospheric origin. An atmospheric emitting layer which is uniform in brightness and thickness as seen from the center of the Earth produces a systematic increase of intensity toward the horizon for an observer on the surface of the Earth. An example of the change of intensity of airglow 5577 with zenith distance for the average of twelve nights at Fritz Peak, Colorado, is shown in Figure 1. That the early investigators were probably correct in attributing the phenomena to the Earth's upper atmosphere is indicated by the close agreement of the theoretical curve and the observational points in Figure 1.

After the initial discovery, our knowledge of the airglow was augmented by: (1) the identification of the 5577 green radiation as a forbidden transition of atomic oxygen, (2) the discovery and identification of the sodium D lines, (3) the discovery and identification of two red lines (6300 A and 6363 A) due to forbidden transitions of atomic oxygen, and (4) the discovery and identification of a complex system of molecular bands (chiefly in the near infrared) due to hydroxyl (OH). The hydroxyl bands are intrinsically so strong that, if they were concentrated in the visual region of the spectrum, they would be as bright as a prominent aurora and would constitute a permanent twilight.

The height of the airglow—There are three methods for estimating the effective height of the airglow: (1) by a night firing of a rocket through the emitting layer, (2) by triangulation between two ground stations, and (3) by the increase of intensity toward the horizon. There have been concentrated attempts by all three methods in the case of 5577 and a height of about 100 km is consistent with all the data.

In Figure 2 is reproduced a plot of 5577 and of sodium D nightglow intensity with height from a recent rocket firing reported by *Koomen, Scolnik,* and *Tousey* [1956] showing a sharp drop-off between 90 and 100 km for 5577 and between 80 and 90 km for sodium D. This isolates the 'layers' between these limits.

In Figure 3 are shown some results on triangulation between Cactus Peak, California, and Palomar Mountain [*St. Amand, Pettit, Roach* and *Williams,* 1955]. At each station photometers scanned the sky systematically dur-

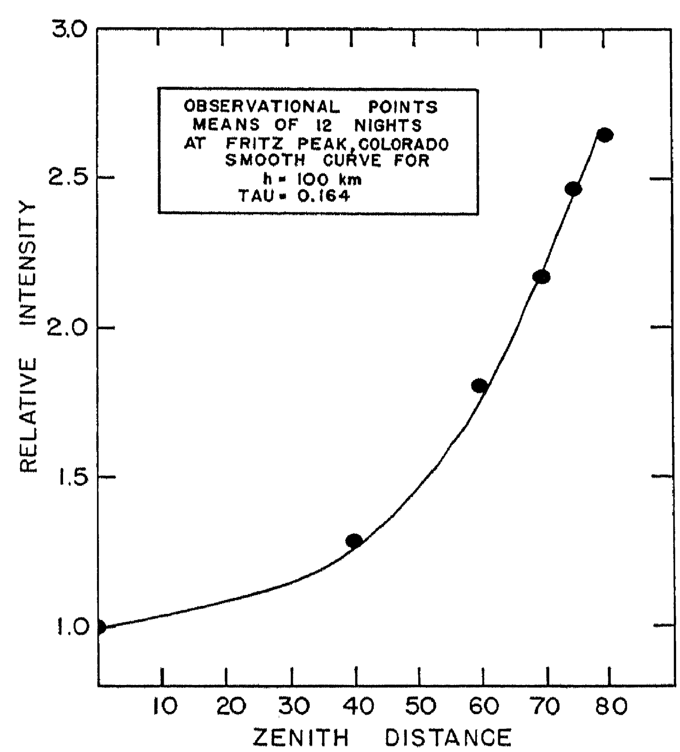

Fig. 1—Change in intensity of airglow 5577 with zenith distance; the smooth curve corresponds to an emission height of 100 km and an extinction coefficient, tau, of 0.164

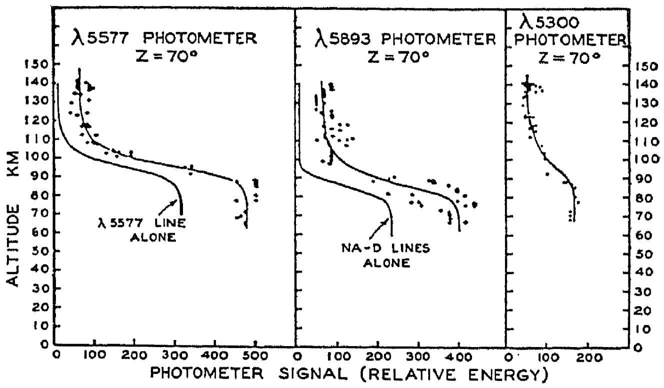

FIG 2 — Variation of airglow intensities with height from a rocket flight, according to *Koomen, Scolnik,* and *Tousey* [1956]

ing the night and recorded the changes of intensity. These intensity changes were correlated for a number of combinations of intersecting lines of sight at various heights above the Earth's surface. The correlation of the intensity changes is shown as $\Sigma d^2/n$ in Figure 3 from which it is seen that the best correlation occurs at a height near 100 km. Results (not yet published) obtained for the two stations, Sacramento Peak, New Mexico, and Fritz Peak, Colorado, give similar heights.

The third method of estimating airglow heights, the rate of increase of intensity toward the horizon is difficult to apply. As a matter of fact, the deduced height is critically dependent on a nice knowledge of the extinction coefficient of the lower atmosphere. In a current study of the problem, *Roach, Megill, Rees* and *Marovich*

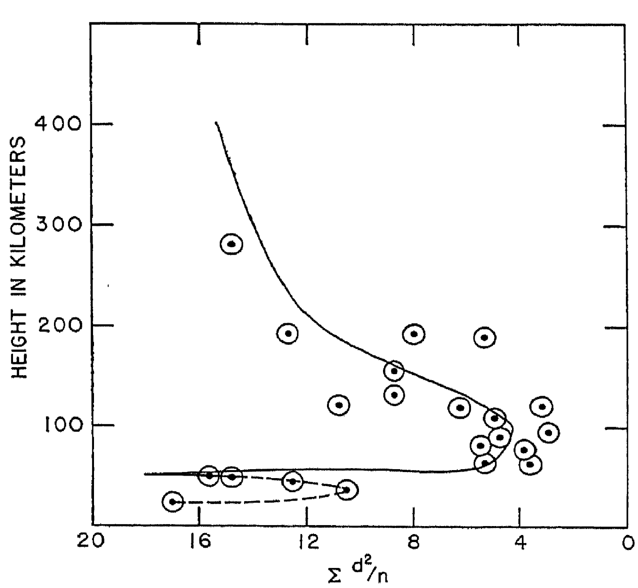

FIG. 3 — Results of triangulation between Cactus Peak and Palomar Mountain according to *St. Amand, Pettit, Roach,* and *Williams* [1955]

[1958] have analyzed the observations during twelve nights at Fritz Peak. We have found that, if we assume the extinction coefficient of the lower atmosphere is constant from night to night, the mean height is about 100 km but the range among the nights is between 51 and 136 km. We prefer the alternative possibility that the extinction coefficient is variable and the height is sensibly constant near 100 km.

In summary the height of the night airglow 5577 now seems to be established. For the other radiations the case is not so clear. The sodium D layer was observed by a rocket flight near 85 km (Fig. 2). The OH layer is probably a little lower (near 70 km) but a rocket confirmation of this would be very useful. According to *Heppner, Stolarik,* and *Meredith* [1957] a recent rocket flight indicates that 6300 originates higher than 163 km.

The changes of intensity with time—All airglow observers have noted the intensity variations of the airglow. In general, very fast variations of a minute or less have not been reported probably because the observing techniques have been too sluggish to detect them. Sky coverages every ten or fifteen minutes are common and during a given night the intensity of 5577 may vary over a two-fold or three-fold range. Often the entire sky visible to a given observer goes through synchronous variations showing that the phenomenon is a large scale one of several hundred kilometers (Fig. 4). On occasion, however, the various regions of the sky go through quite different variations during a night as on October 1–2, 1956 (Fig. 5).

In order to visualize the photometric history of an entire night, it is convenient to make circular plots of the entire sky at intervals during the night. The outer circle (Fig. 6) corresponds to a distance along the Earth's surface of about 470 km from the observer who is in the center of the circle. In preparing these isophote maps

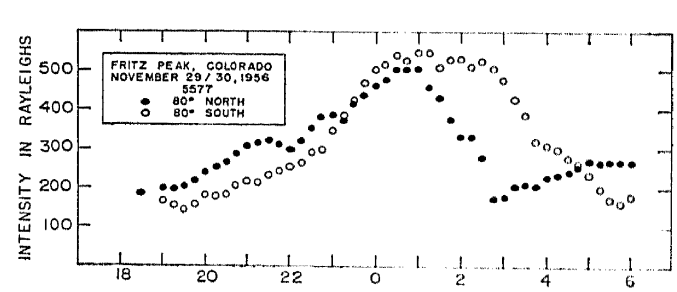

FIG. 4 — Synchronous variations of 5577

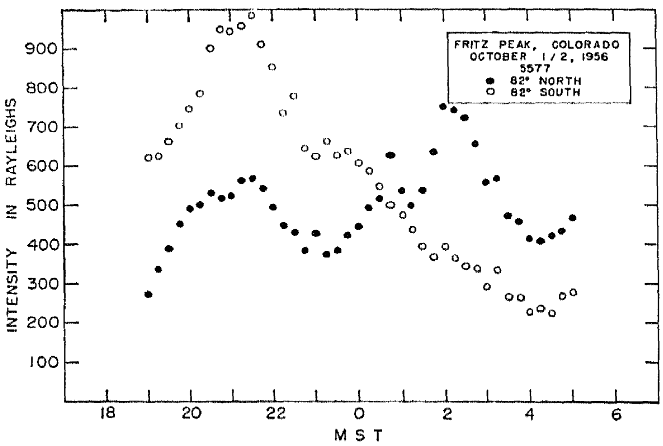

FIG. 5—Non-synchronous variations of 5577

the general increase of intensity toward the horizon has been eliminated.

On the night of October 1–2, 1956, the airglow was especially bright in the south during the early evening (20h and 21h MST), actually about the brightness of a faint aurora. Between 20h and 22h, one has the impression that a strong maximum region has moved southward outside the limits of our observing circle at Fritz Peak. By 23h and midnight, the general level of brightness is significantly lower but the south is still brighter than the north. At 01h, a new localized region of brightness appears in the north which develops significantly by 02h and is slightly weaker by 03h. The 'activity' during this night illustrates the fact that the airglow is a dynamic phenomenon of the upper atmosphere.

The physical significance of these complex changes is not known but in a few cases where more or less discrete patches have been followed, the apparent velocity of motion is about 70 m/sec (150 mi/hr). These motions may, of course, be caused by progressive movements of excitation changes in the upper atmosphere but it is interesting to speculate that they may indicate actual wind motions. If this is true then we have a powerful tool for the systematic study of dynamical conditions in the 100 km region during IGY.

Evidence for a latitude-seasonal effect—From the numerous empirical facts known about the night airglow, I have selected a very suggestive result for discussion at this meeting. Several years ago, *Barbier, Dufay,* and *Williams* [1951] noted that, at the Haute Provence Observatory in southern France, there was a strong tendency for the airglow 5577 to be brightest near the southern horizon. Using published data from Sacramento Peak and Cactus Peak and accumulated unpublished data from Fritz Peak, I have made a comparison of the north versus south tendency for these three stations plus Haute Provence. When the results are plotted as histograms as shown in Figure 7, it is seen that there is an indication of a region of maximum intensity at about 38° north latitude. It has been suggested that this might be a secondary, weak, auroral zone and in Figure 8 the same histo-

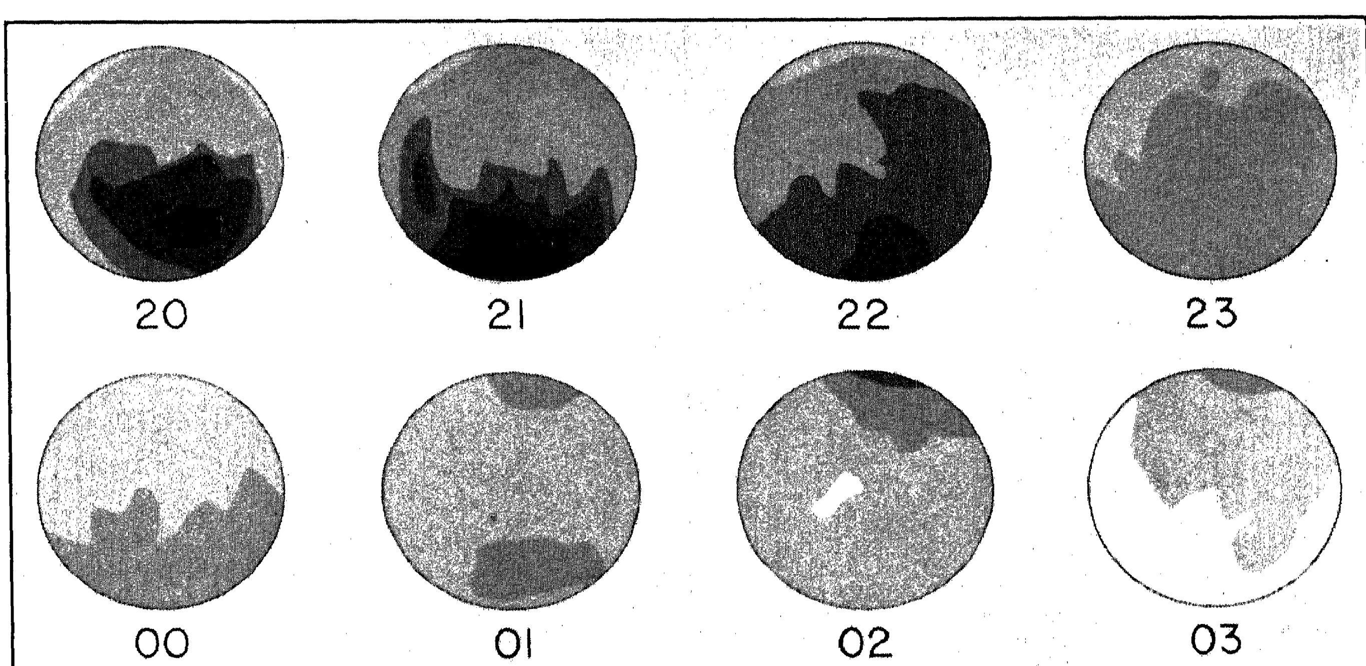

FIG. 6—Circular plots of the entire sky, Fritz Peak, 5577A, Oct. 1–2, 1956

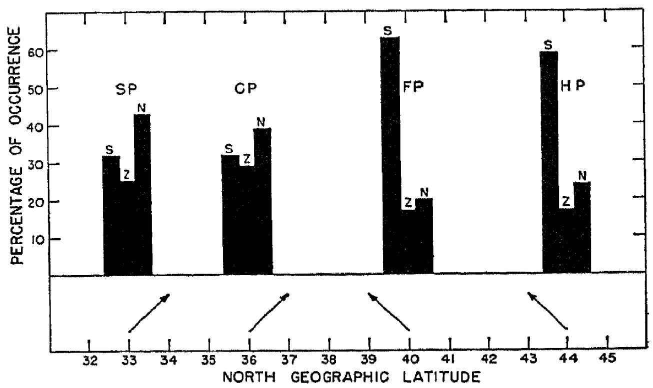

FIG. 7 — Histogram of the relationship of the percentage of occurrence to the geographic latitude

grams are shown against geomagnetic latitude where 44° geomagnetic latitude seems to be indicated as the maximum region. Is it just a coincidence that the co-latitude in this case (46°) is exactly twice the co-latitude of the primary auroral zone (23°)?

This apparent latitude maximum turns out to be a complex matter. In Figure 9, is shown a plot of the ratio of intensity at Fritz Peak of 5577 in the extreme north (80° north zenith distance) to the extreme south (80° south zenith distance) plotted against the day in the year. A definite seasonal variation is evident with the north brighter in the summer and winter, and the south brighter in spring and autumn. The explanation for the southern tendency at Fritz Peak lies in the fact that the spring and autumn southern tendency persists through a larger fraction of the year than the summer and winter northern tendency.

In Figure 10 is shown a composite sketch of

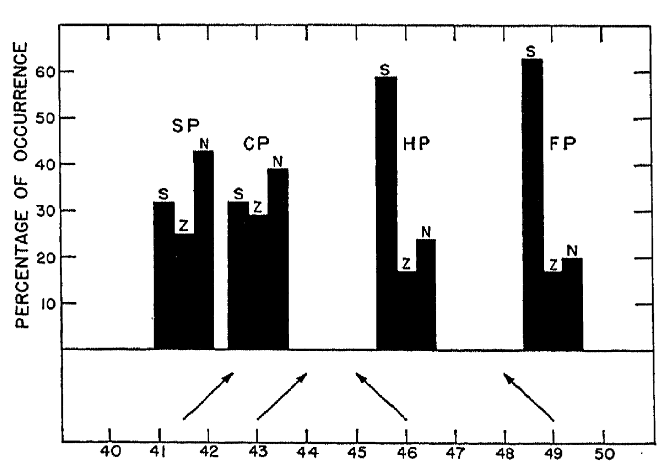

FIG. 8 — Histogram of the relationship of the percentage of occurrence to the geomagnetic latitude

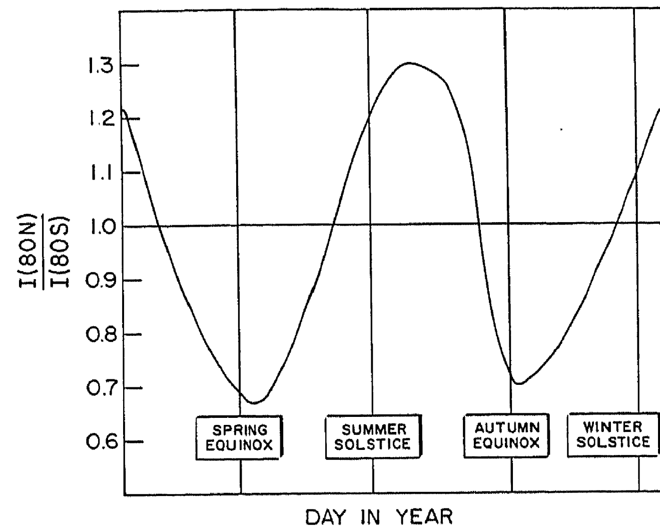

FIG. 9 — Relationship of the ratio of intensity of 5577, north/south to season

the seasonal effects at three of the four stations included in the present discussion. The evidence suggests the existence of a large scale latitude-seasonal variation in airglow 5577.

The existence of a half-year periodicity is puzzling. One speculative suggestion is that we are dealing actually with two phenomena which are schematically represented in Figure 11. According to this picture each of the two phenomena goes through a single annual cycle but an observer at a mid-latitude sees a semi-annual cycle as the two excitation waves appear, disappear, and reappear. If, as was suggested earlier, the movements during a night are

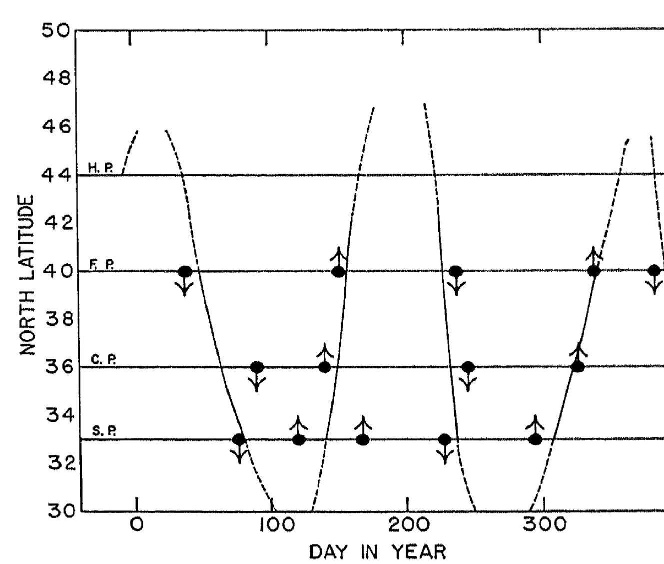

FIG. 10 — Composite sketch of seasonal effects; the arrows indicate the dates on which the maximum brightness goes from north to south (arrows pointing downward) or from south to north (arrows pointing upward)

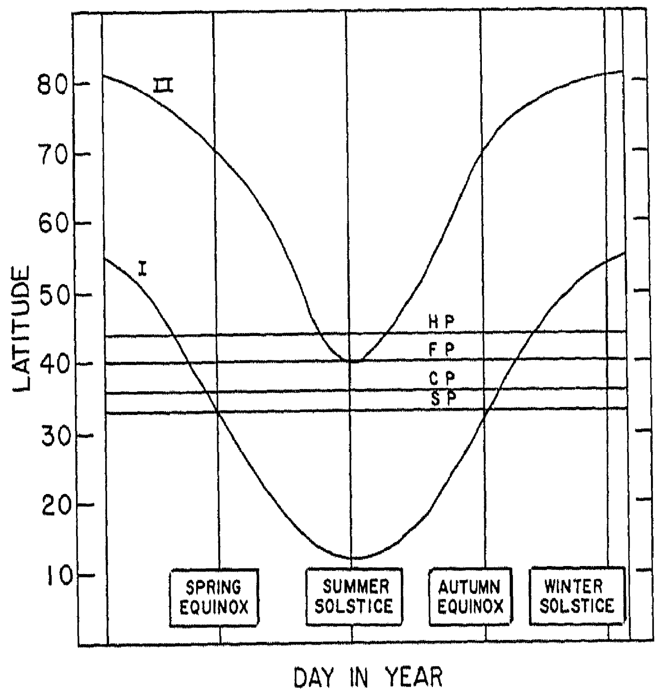

FIG. 11 — Suggested double mechanism to explain the seasonal variation of 5577

evidence for wind motions, could it be that the large scale latitude-seasonal variations are due to changes of wind systems on a synoptic basis? If so, the upper atmosphere must have complex wind systems comparable to the jet streams of the troposphere.

The scale of airglow phenomena—It is sometimes useful to give order-of-magnitude considerations to a physical phenomenon. For example, in the case of the airglow it would be interesting to consider (1) what are its typical physical dimensions, and (2) what is a representative time to describe the intensity variations.

From Figure 6 we deduce that the large airglow features are at least as large as the amount of the upper atmosphere included by a single observer. We thus come to an approximate dimension of 1000 km or 10^8 cm.

The temporal variations that occur seem to span several hours which leads us to a time scale of about 10^4 sec.

Although these figures are crude they do serve as a guide in selecting the general approach to any theory which attempts to cope with the synoptic features of the airglow.

Conclusion—The airglow first appeared on the scientific horizon as an isolated fact of nature of primarily academic interest. For some time it was thought of as a quiescent glow in the Earth's upper atmosphere. Current studies show, however, that it is a complex phenomenon with dramatic temporal and spatial variations. The physical significance of these dynamic changes is not now apparent, making the study of the airglow during the International Geophysical Year one of compelling interest.

References

BARBIER, D., J. DUFAY, AND D. R. WILLIAMS, Recherches sur l'emission de la raie verte de la lumiere du ciel nocturne, *An. Astrophysique,* **14**, 399, 1951.

HEPPNER, J. P., J. D. STOLARIK, AND L. H. MEREDITH, Rocket measurements at WSPG, New Mexico, July 5, 1956; pt A, Altitude distribution of nightglow emissions (abstract), *Trans. Amer. Geophys. Union,* **38**, 394, 1957.

KOOMEN, M., R. SCOLNIK, AND R. TOUSEY, Distribution of the night airglow (OI) 5577A and NaD layers measured from a rocket, *J. Geophys. Res.,* **61**, 304–306, 1956.

ROACH, F. E., L. R. MEGILL, M. H. REES, AND EDWARD MAROVICH, The Height of Nightglow 5577, *J. of Atm. Physics,* **12**, 171, 1958.

ST. AMAND, P., H. PETTIT, F. E. ROACH, AND D. R. WILLIAMS, On a new method of determining the height of the nightglow, *J. Atm. Terr. Phys.,* **6**, 189, 1955.

Central Radio Propagation Laboratory, National Bureau of Standards, Boulder, Colorado

The Rocket as a Research Vehicle

P. H. Wyckoff

Introduction—Ever since man first gazed aloft at the stars at night, the far reaches of outer space have stimulated his imagination with their awe-inspiring vastness. He has dreamed of soaring aloft on powerful wings and exploring the heavens and the stars. According to Greek mythology, this ambition prompted Daedalus to build a set of wings for his son, Icarus, and fasten them to the boy with bands of wax. The wings worked successfully but, unfortunately, Icarus flew too close to the Sun, which melted the wax on his wings. Icarus' headlong plunge to Earth was man's first indication that the study of upper air physics was vital to his survival as an airborne creature. Today the melting point of wax is no longer a problem, but many more and vastly more difficult problems face us in our steady climb upward for knowledge. We know, for instance, that if we fly to an altitude of 100,000 ft above the Earth, we will have over 99 pct of the Earth's atmosphere below us. But what lies above us in that vast area which contains less than one per cent of the Earth's atmosphere?

In this sparse region of our atmosphere we know that the rays of our Sun first strike the gaseous envelope surrounding the Earth and produce chemical and ionic changes of fantastic complexities. Under solar bombardment, the outer atmosphere becomes a chemical cauldron of active oxygen and nitrogen atoms mixed with atoms of sodium, hydrogen, and other elements to produce an atmosphere quite unlike the normal air which we are accustomed to breathing on the surface of our planet. This chemical cauldron produces the ionosphere, which is responsible for reflecting radio energy around the curvature of the Earth and makes long-distance radio communication possible. It is the home of the aurora which produces the beautiful northern lights in the sky, and is a vast storehouse of solar energy which is given out at night as a dim but measurable light of the night sky. It is a region of fascination for the physicists and chemists who study our atmosphere so that we may some day understand its secrets and use them for the benefit of mankind. At the present time, we can only speculate upon the many activities which take place in the upper atmosphere. We are not even certain of the density, pressure, and temperature which exist 300 mi above the Earth, and our present estimates may be in error by a factor of a hundred or more in some cases.

When we consider the problems of flight of the Earth satellites soon to be launched for the International Geophysical Year, we realize that an accurate knowledge of the density of the air, the intensity of the incoming solar radiation, the frequency and momentum of meteoric particles, the scattering of light in the Earth's atmosphere, and many other factors are already vital information in the design of such a vehicle before it even leaves the ground. Fortunately, we are able to make predictions of these quantities by indirect means such as the observation of meteor trails, the scintillation of stars, the absorption of specific wave lengths of the Sun's rays filtering down through our atmosphere, the scattering of light from powerful searchlight beams probing up to 60 km and many other scientific means of deduction. It is obvious, however, that the greatest need is for a means of lifting our scientific measuring devices up into the atmosphere where the measurements can be made directly.

One of the first devices known to man was the balloon, and for altitudes up to 150,000 ft the present day balloon is admirably suited for carrying scientific instruments aloft. For altitudes above 150,000 ft, however, the research rocket is the only answer.

The Research Rocket

Sizes of rockets differ in payload to be carried and altitude to be reached in almost the same ratio as a Piper Cub aircraft differs from a B-36. Each has its peculiar advantage and reason for being. Small, inexpensive rockets may lift ten-pound loads to 250,000 ft, while large rockets can lift 200-lb loads to 300 mi with no effort but considerably greater cost. Today it is purely a matter of design and the amount of money which can be invested to obtain the performance needed.

Rockoon—To obtain the information needed for the International Geophysical Year, three standard systems of rockets are being used. The smallest is the Rockoon, which is a solid-fuel rocket approximately six inches in diameter and 12 ft long. In its nose it carries some 20 lb of electronic devices which obtain information about the upper air and radio this information to the ground while in flight. The Rockoon is carried to 80,000 ft riding in a sling under a huge plastic balloon and at the proper moment the rocket is fired electronically and soars upwards to an altitude of 60 to 70 mi above the Earth. Over 85 of these Rockoons will be fired during the IGY in regions stretching from the Arctic to the Antarctic to obtain information on cosmic ray particles at high altitudes and to obtain information on ultraviolet and x-rays emitted by the Sun during periods of solar flares.

Nike-Cajun—The second type of rocket finding wide application in the US IGY program is the Nike-Cajun. This is a two-stage rocket launched from the ground, and has the capability of reaching 100 mi in altitude with 40 lb of scientific equipment. The first stage is a solid-fuel Nike booster. Its function is to lift the second stage containing a smaller rocket, similar in size to the one used in the Rockoon, to an altitude of over 100,000 ft, after which the second stage fires in the thin air of less than one-hundredth the density of sea level and the rocket darts upward to 100 mi above the Earth. At the peak of its velocity the missile is traveling at close to five times the velocity of sound. After the propellant has burned out, the scientific instrumentation goes into operation and sends its measurements back to the ground by radio telemetering. Approximately 65 of these will be flown during the IGY.

Aerobee—The third type of rocket to be fired by the U. S. scientists for the IGY is the Aerobee and Aerobee-Hi. It is a liquid-fueled rocket carrying approximately 50 gal each of analine and fuming nitric acid to propel it. This rocket is approximately 15 inches in diameter and 24 ft long, weighing almost a ton when fully instrumented and fueled. It is thrust out of a 100-ft tower by a solid fuel booster to gain its initial velocity and direction, and then the liquid fuel motor takes over and drives it for some 43 sec during which it attains a peak velocity about 4.5 times the speed of sound. This rocket has the capability of lifting some 150 to 200 lb of scientific instrumentation to altitudes between 60 mi and 200 mi, depending upon the model used. Some 42 of these rockets will be launched by the U. S. scientists during the IGY.

Measurements

Measurement of the upper air from a rocket traveling at velocities of 4 to 5 times the velocity of sound is no trivial accomplishment, and the present techniques are the results of many years of intensive experience gained since the launching of the first V-2 in New Mexico. Many early rocket flights were failures before these techniques could be developed which are to be used for the IGY in the next eighteen months. One might say that the IGY, in the rocket field, is the culmination of over ten years of intensive and often heart-breaking experience since the days of the first flights of the V-2's fired for scientific purposes.

Atmospheric structure—One of the most obvious series of measurements to be made is the vertical distribution of pressure, temperature, and density of the atmosphere. Experience has shown this to be also one of the most difficult measurements to make accurately. The terrific speed of the rocket produces high temperatures on any probe which is extended into the air stream, and completely masks the true temperature of the air. Today we are still unable to measure air temperature directly, but must calculate it from some other measured parameter such as pressure, density, or velocity of sound. The measurement of pressure in itself is no easy problem, since in the more dense regions of the upper air, corrections must be made for the momentum of the air which is scooped out by the rocket's measuring gages. Thus, the velocity of the rocket creates a dynamic pressure of its own which must be compensated for before the pressure of the atmosphere can be determined. At very high altitudes a new problem arises, since the rocket is now traveling in what may be considered in the laboratory as a very good vacuum. At these altitudes, the skin of the rocket exudes gases which have been trapped in the pores of the metal itself, and surrounds the rocket with an atmosphere of its own making.

This problem of measuring atmospheric pressure through the screening rocket gases has been partially solved by various ingenious techniques.

One of these methods involves sealing off the rocket with airtight compartments so that internal gases in the rocket cannot seep out. The rocket is then made to rotate so that the pressure-measuring orifice is first exposed to the full blast of the air stream, and then rotates to a shielded position where it is protected from the air blast. The resulting modulation in pressure can be interpreted in terms of true ambient pressure.

Another ingenious method is to eject a small seven-inch sphere (Fig. 1) from the rocket when it has reached the top of its trajectory. The sphere is accelerated downwards by gravity in free fall, but is also decelerated by the density of air through which it is falling. The drag of the air on this falling sphere is measured by a small accelerometer inside the sphere and is transmitted to the ground by a small radio transmitter complete with batteries which is also mounted inside the sphere. The values of drag are then computed to obtain the density of the air through which the sphere is falling.

Another technique for measuring temperature and winds in the upper air uses a rocket containing some eighteen explosive grenades which can be ejected one at a time from the rocket at timed intervals while the rocket is passing through the region to be measured. On the ground an array of sensitive microphones is set up in the form of a cross with approximately 3000 ft from microphone to microphone. Each microphone hears and records on film the explosion of the grenade in the high upper air but, because of the position of the microphone on the ground, each microphone hears the sound at a slightly different time. By noting the time taken for the sound to travel through the air from the rocket to the ground, the average temperature of the air can be computed for that particular sound path. Successive grenade bursts give further information concerning average temperatures from higher elevations of burst, and the difference in the average velocity of sound from two successive bursts will yield a measurement of the average temperatures of the

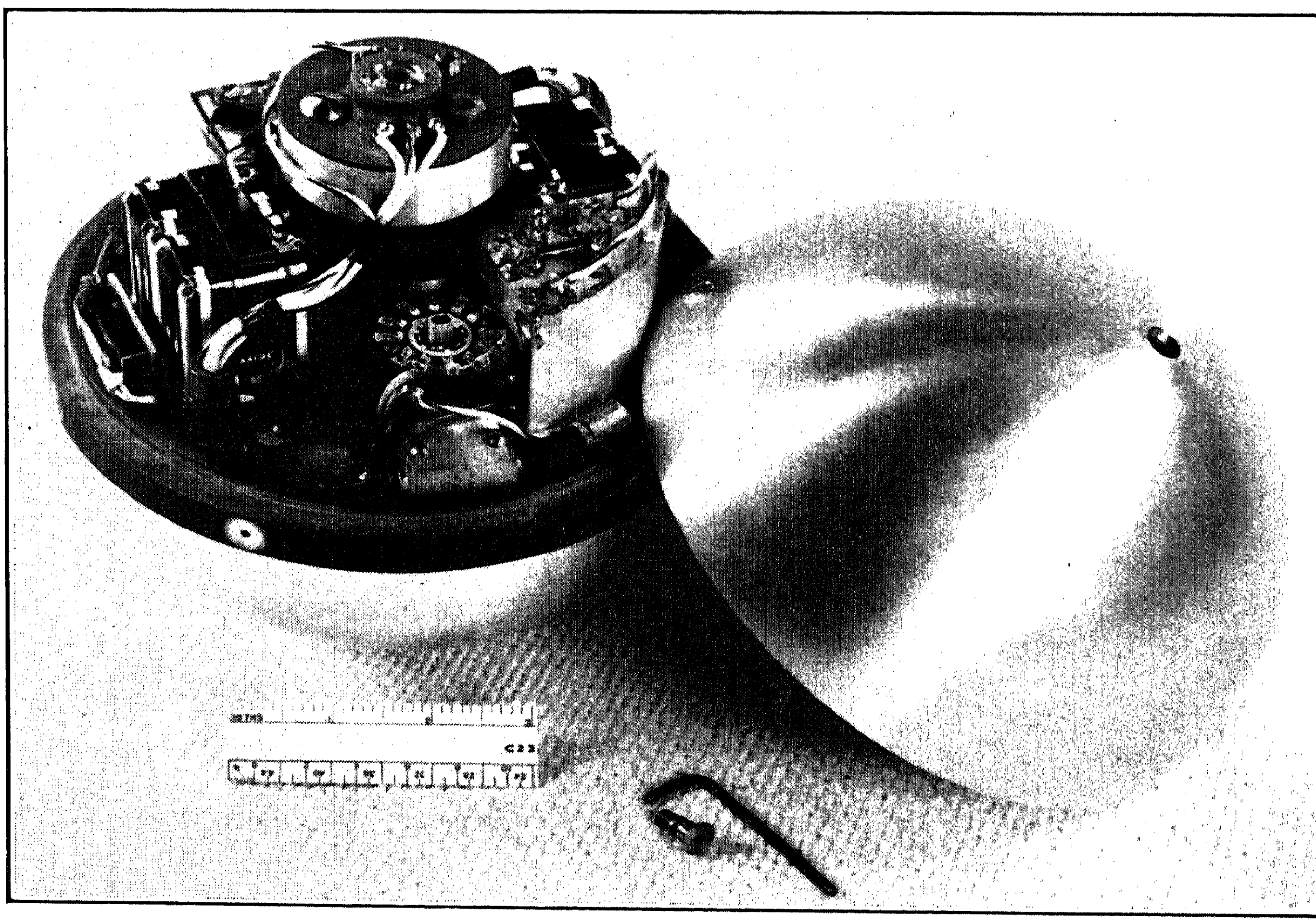

FIG. 1 — Seven-inch sphere which is ejected from rocket to measure density of the upper atmosphere; top of sphere is removed to show accelerometer and miniature telemetering transmitter inside sphere (designed for the U. S. Air Force by the University of Michigan)

upper atmosphere for that particular segment of air through which the rocket has just passed. The difference in arrival time of the sound at the various microphones on the ground yields a measure of the average upper level wind velocity and direction.

Ionized layers—Measurements of the density and location of the ionized layers of the ionosphere are very important to an adequate understanding of its formation and for establishing a method for predicting radio fadeouts during periods of activity on the surface of the Sun. The measurement of ion density in the ionosphere from rockets depends upon the fact that radio waves in the vicinity of 6 to 12 megacycles are slowed up in passing through the ionosphere in proportion to the density of the ion layer through which they must pass. On the other hand, higher-frequency radio waves, say 200 megacycles, are not appreciably affected in passing through the same ionized layer. By transmitting radio energy from the rocket to the ground simultaneously on both high and low frequency, the lower-frequency signals are received several millionths of a second later on the ground than the higher-frequency signals, and the density of the ionized layer through which they both passed can be computed from this difference in arrival time.

Solar radiation—Since the behavior of the upper atmosphere is wholly dependent upon the strength and wave length of the radiation being emitted by the Sun in the ultraviolet and soft x-ray portion of the spectrum, it is important to measure this radiation directly from the rocket. Since this radiation is quickly absorbed in the outer fringes of the Earth's atmosphere, none of it ever reaches the ground and, consequently, cannot be measured even at the highest mountain top observatories. Only the rocket is capable of carrying the necessary spectrometric equipment to altitudes of 100 mi or more where the ultraviolet light from the Sun is still relatively unabsorbed and can be separated into its component wave lengths and recorded on film. The rocket, however, is not a stable platform near the peak of its trajectory, and almost always begins to spin and yaw since the air is so thin that the rocket fins are no longer effective in maintaining stable flight. To insure that the spectrograph will always 'look' at the Sun, a stable platform has been developed to point the spectrograph

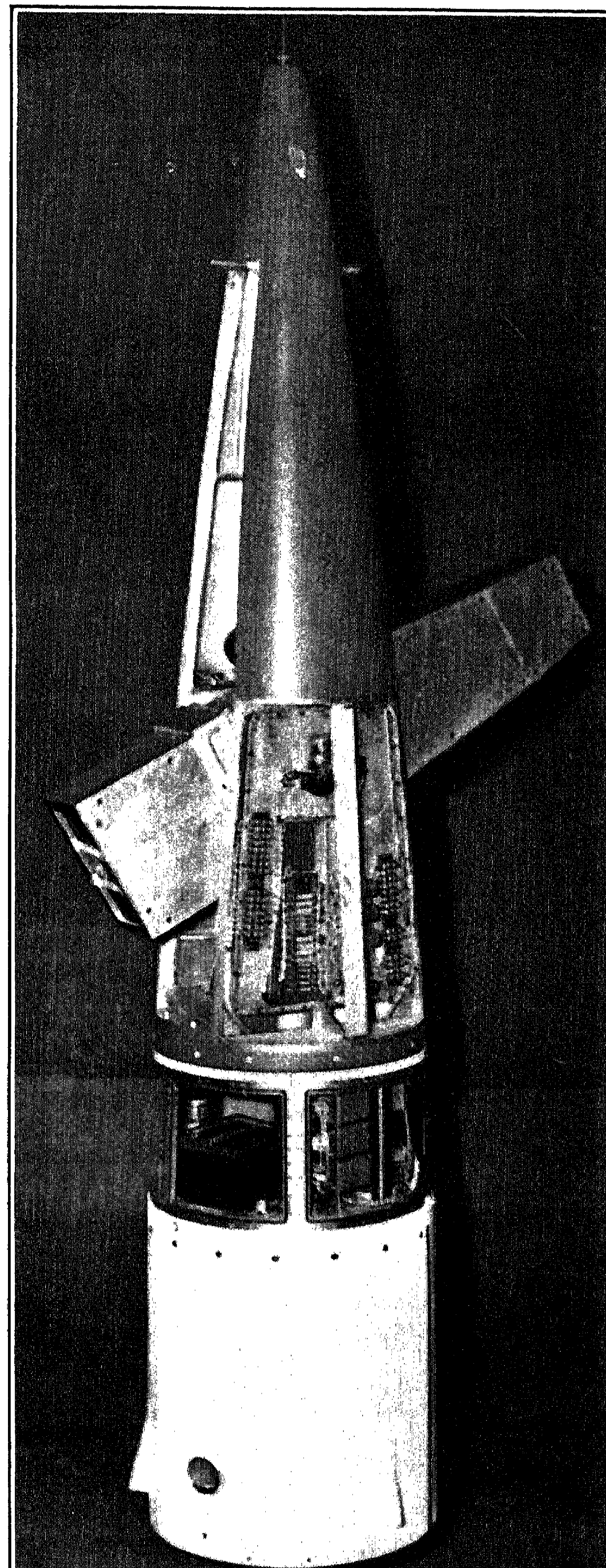

FIG. 2 — A biaxial pointing control which automatically maintains the entrance slit of an ultraviolet spectrograph pointed at the Sun regardless of the altitude or roll of the rocket while in flight (designed for the U. S. Air Force by the University of Colorado)

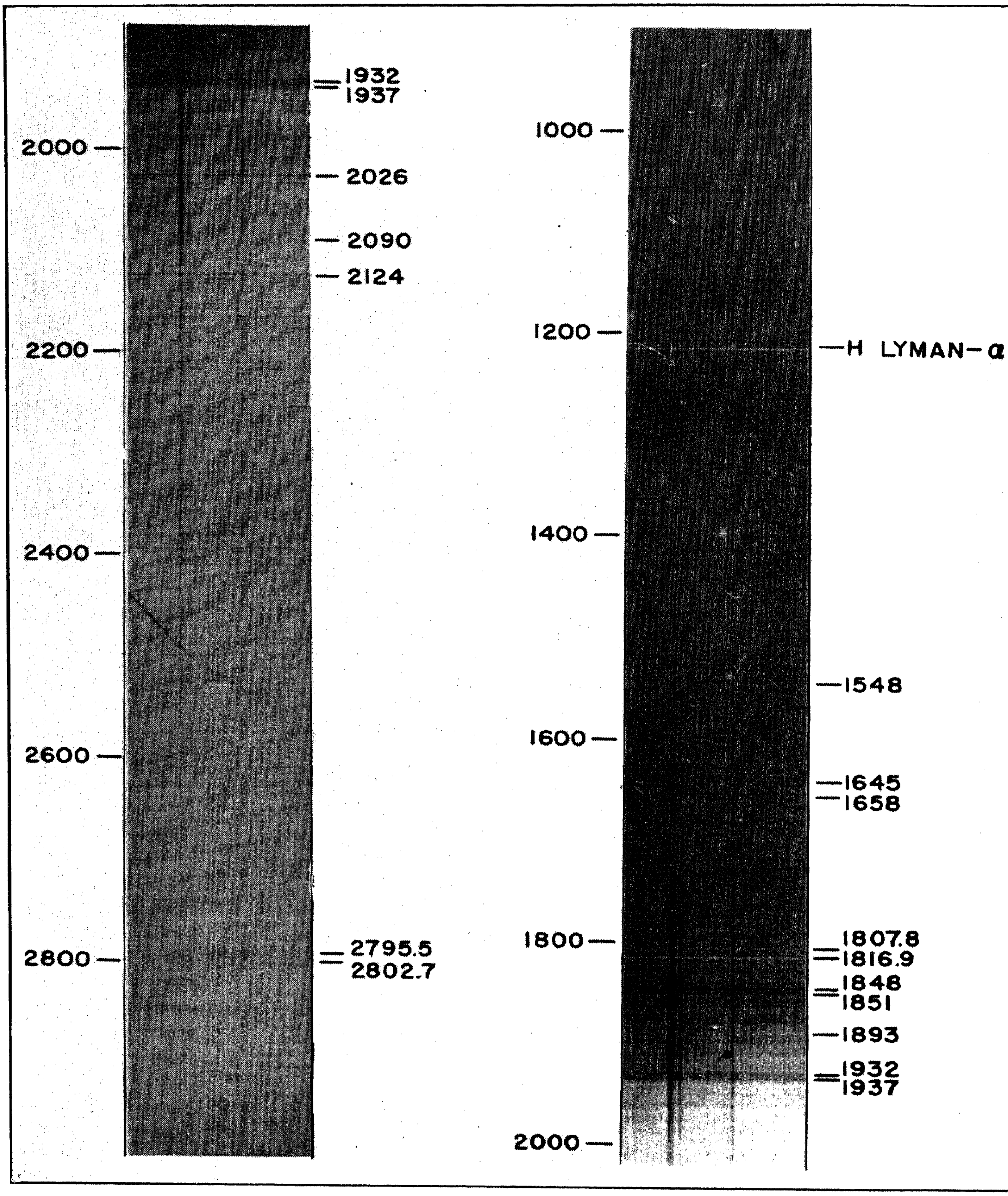

FIG. 3 — Solar spectrum recorded at an altitude of 112 km over New Mexico on March 29, 1955 (exposure, 4.6 sec) by Geophysics Research Directorate, AFCRC

at the Sun regardless of the gyrations of the rocket. It consists of a swivel nose on the end of the rocket which holds an arm which can be moved up or down as required (Fig. 2). Photocells are mounted on the end of the arm which pick up energy from the Sun and send corrective signals to little electrical motors which control the swivel and the lowering or raising of the arm. Thus when the photocells first see the Sun, they lock on to that direction and actuate the guiding motors to hold the entrance slit of the spectrograph on the Sun within a few minutes of arc. Without the biaxial pointing control, spectrograms of the Sun would be purely a matter of chance as the spectrograph happened to sweep by as the rocket gyrated. After the spectrograms are obtained, the nose cone is separated from the rocket and floated back to the ground by means of a parachute. The films are then developed and the secrets of solar radiation in the fringe of space are made available to the scientist for study (Fig. 3).

As we mentioned before, the outer fringes of the Earth's atmosphere form a huge chemical reaction chamber where solar radiation furnishes the energy for the synthesis of many compounds which store solar energy in much the same way as the lead storage battery stores electrical energy in chemical form. Some day man may become ingenious enough to tap this vast reservoir of energy, but to do this, he must first understand it. Many of these reactions which store energy gradually decay and give back energy in the form of light of a wave length characteristic of that particular reaction. Such light is known as airglow, and its wave length is an indication to the scientist of the form in which the energy was stored. During the International Geophysical Year, rockets will also be fitted with sensitive photocells which will detect the telltale light from the airglow and tell the scientist what wave lengths are present and from which altitudes they originate. From this information, the upper air scientist can reconstruct in his own laboratory the exact reactions which occur and study means of using this information to advantage. Even today scientists have derived enough information on the distribution of atomic oxygen at 60 mi to consider the design of a rocket which would be propelled entirely from stored solar chemical energy. This would be essentially a satellite operating on stored solar energy in the atmosphere instead of pure momentum, as in the case of the present satellite vehicle.

Magnetic fields—Measurements will also be made of the magnetic fields which exist in the high upper atmosphere which are produced by rings of charged particles circling the earth at very high levels. It is believed that these particles are expelled from the Sun and are trapped into a circular orbit by the Earth's magnetic field. Fluctuations in the Earth's magnetic field have been recorded for many years, and are believed to be produced in this manner. Magnetic storms which produce a blackout of all forms of electrical communication are well known in the Arctic, and measurements of these magnetic fields can now be made in rockets in order to better understand their behavior. It is hoped that these measurements will help us to predict magnetic storms in the future by the observation of unusual activity on the surface of the Sun which is responsible for bombarding the Earth during periods of solar unrest.

Conclusion

The benefits of the rocket measurements to be made by the United States scientists at Ft. Churchill, Canada; White Sands, New Mexico; Guam; and from shipboard from almost pole to pole are almost incalculable. They will be supplemented by similar measurements made from rockets by Australian, British, French, Japanese, and USSR scientists. For the first time the scientists of the world are making a systematic and concerted attack on the mysteries of the upper atmosphere by the use of rockets, and the result could very well bring the conquest of space within our grasp in the not too distant future. Perhaps within the next twenty years man will learn to duplicate the feat of Icarus but, with his increase in knowledge, he will learn to survive where Icarus failed.

Aerosol Physics Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, L. G. Hanscom Field, Bedford, Massachusetts

The Pre-IGY Rocket Program of the United States

HERBERT FRIEDMAN

Introduction—Our knowledge of the atmosphere and its behavior under the influence of solar radiation has been gained by a combination of direct and indirect observations. Until ten years ago, no direct measurements were available. The remarkable engineering developments in rocketry which took place in Germany during the war presented scientists for the first time with the possibility of transporting measuring equipment directly into the high atmosphere. With the conclusion of World War II, German V-2 rockets were brought to this country and thus began the upper atmosphere rocket research program. Since then a variety of rockets have been used to study the pressure, temperature, density and composition of the upper atmosphere, the solar spectrum in the extreme ultraviolet and x ray regions, the ionosphere, the Earth's magnetic field, auroral particles, and cosmic rays.

The V-2 was a large rocket, about 42 ft long and weighing nearly 15 tons at take-off. At the time they were made available for research, the existing V-2's had already deteriorated considerably. After about 50 had been fired, the V-2 rocket was abandoned by most experimenters as too unreliable a vehicle in which to risk an elaborate experiment. By that time, both the Viking and Aerobee rockets had been developed. The Aerobee, a liquid propellant rocket, about 25 ft long weighing about 2000 lb, quickly became the work horse of the upper-atmosphere research program because it was much less expensive than the Viking and so much less complicated that its chances of successful performance were proportionately enhanced. About 160 Aerobee flights have been made to date; these have produced by far the major contribution to our present knowledge of the upper atmosphere and of solar radiation.

In recent years, considerable interest has developed in the use of small solid-propellant rockets with capability of carrying 20- to 50-lb payloads into the ionosphere. A pioneering accomplishment in this direction was the development, by James A. Van Allen, of the Rockoon, a combination of Deacon rocket and Skyhook balloon. The Deacon is a six-inch, 200-lb, solid-propellant JATO bottle. Fired from the ground, it could barely achieve a peak of 30 km. A 70-ft helium-filled balloon can raise it to 80,000 ft, and fired from that level, the rocket can carry a 20-lb payload to 120 km.

Another means of assisted take-off for small rockets is the Nike booster. The combination of a Nike booster and a Cajun rocket has achieved altitudes in excess of 100 mi. A major effort was made to perfect this technique for use in the IGY, since it permits great mobility and simplicity in launching.

The IGY is an exciting climax to a decade of upper-atmosphere research with rockets. Almost as many experiments will be flown in the 18-month period as were attempted in all the past ten years. Rockets will be launched from a major new location in the auroral zone at Fort Churchill, Canada, established by Canadian and United States cooperation, and from ships and island locations scattered over the world. This effort constitutes a grand expansion of the geographic boundaries of rocket exploration.

Measurements of the basic atmospheric parameters, pressure, density, and temperature have a prominent role in the IGY rocket program. Virtually all of our present knowledge is confined to the region of the atmosphere above the White Sands Proving Ground (WSPG) in New Mexico. The IGY rockets will search for deviations from the temperate-zone standard atmosphere in both the auroral and equatorial zones. Solar-radiation measurements on the other hand could all be made from WSPG except for the problem of range scheduling. The greatest interest attaches to the emissions of an active Sun, but phenomena such as solar flares cannot be scheduled. Shipboard launching techniques and new range facilities have been developed so that rockets may be fired without restrictions. Much of the scientific interest in cosmic-ray and geomagnetic measurements is concerned with their geographic dependence. Rockets will therefore be launched at latitudes all the way from the Arctic to the Antarctic. With regard to auroral measurements the Ft.

Churchill location is a vitally needed facility, located in the middle of the auroral zone.

In planning the United States portion of the IGY Rocket Program one of the guiding principles was the selection of tried and proven experimental methods. It is true that the IGY instrumentations closely resemble those flown in the past but great advances in rocketry even over the past year have expanded the scope of measurements considerably and introduced many new logistics problems. Small rockets have surged ahead as a practical means of gaining geographic and synoptic coverage at comparatively low cost. The greatly improved performance of the Aerobee-Hi now provides a research rocket capable of reaching the upper limits of the F-region ionosphere in the neighborhood of 200 mi. To perfect these latest techniques in rocketry and instrumentation, a pre-IGY Rocketry Program was carried out over the past year with 24 test flights including 19 small rockets and 5 Aerobees. The purpose of this report is to describe the experiments performed with these rockets and the scientific results deduced from preliminary analyses of the data.

Pressure, density, and temperature measurements—Pressure, density, and temperature are interrelated so that measurements of any two of the quantities enable the third to be computed, provided the molecular composition is known. A variety of rocket techniques are to be used in the IGY program including sound ranging, direct pressure and density measurements, and measurements based on aerodynamic properties of the flying rocket.

The first pre-IGY rocket launching took place at Wallops Island, Va., on July 5, 1956. The rocket, a Nike-Cajun, instrumented to measure atmospheric density, was prepared by members of the Aeronautical Engineering Department of the University of Michigan under the direction of L. M. Jones. This was the first in a series of Nike-Cajun rockets adapted to upper-air sounding purposes jointly by the University of Michigan under sponsorship of Air Force Cambridge Research Center and by the Pilotless Aircraft Research Division of the National Advisory Committee of Aeronautics. The experiment is known as the 'falling sphere.' The rocket rose to 425,000 ft and ejected a seven-inch sphere at 198,000 ft on the upward leg. As a sphere falls through the atmosphere, the increasing air density produces a deceleration force proportional to the air drag. The drag, in turn, can be related directly to the density. Figure 1 is a schematic of the design of the Michigan transit-time accelerometer used to measure the deceleration force on the falling sphere. The bobbin floats in a cavity so shaped that the distance of travel to the wall is the same in any direction when the bobbin is centered. If the sphere were in free fall in vacuum, the bobbin would not move relative to the wall when released. As soon as any drag acceleration is introduced the bobbin moves toward the wall. If the drag increases, the transit time decreases. As shown in the diagram, the sphere carries its own transmitter to telemeter the transit times. In flight tests this instrument was able to measure drag accelerations less than one hundredth that of gravity.

Figure 2 is a photograph of the Nike-Cajun in its launcher at WSPG. Five more Nike-Cajuns were fired by the University of Michigan in October and November 1956 in the North Atlantic Ocean and Davis Straits between latitudes 39°58′N and 64°10′N from the deck of the U.S.S. *Rushmore*, LSD-14 (Fig. 3). These rockets also carried the small-sphere experiment for density. All the rockets exceeded 100 mi in peak altitude and the instrumentation worked well. Data reduction has not yet been completed.

A second group from the University of Michigan, under the direction of N. W. Spencer, pre-

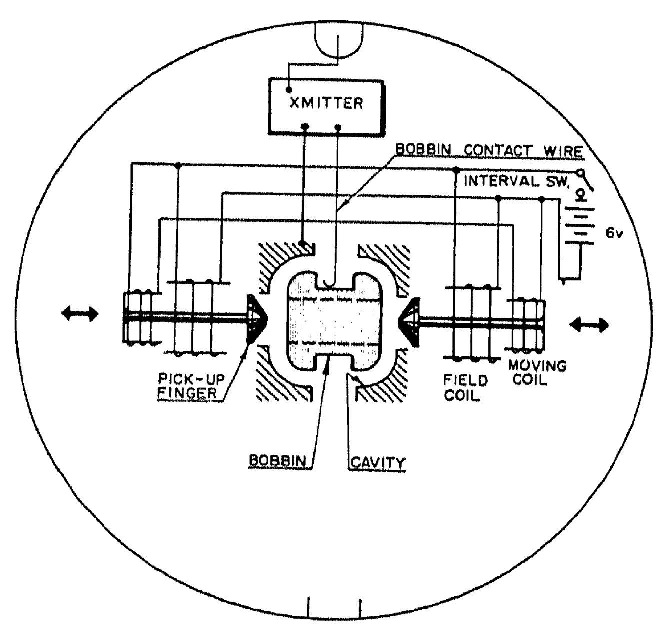

FIG. 1—Diagram of transit time accelerometer in seven-inch sphere

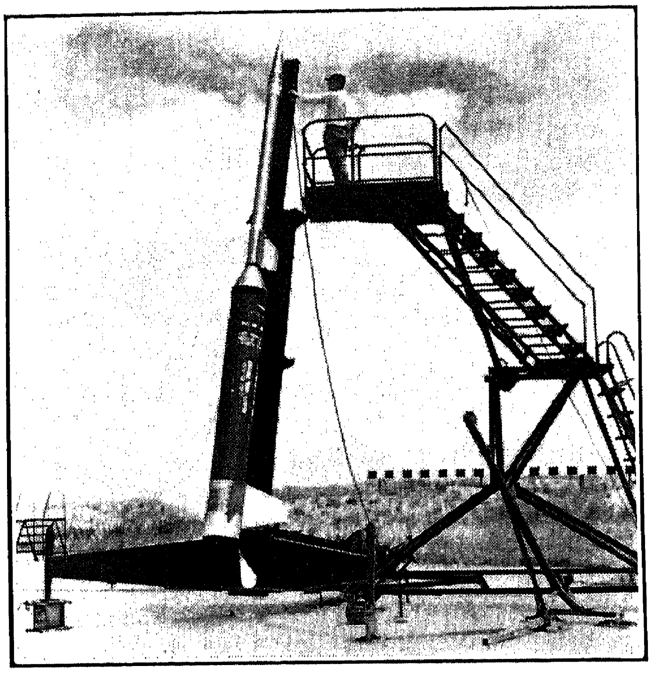

FIG. 2 — Nike-Cajun on launcher at White Sands Proving Ground, N. M.

pared two rockets at Fort Churchill to measure pressure, temperature, and density. This work was performed under contract to the Air Force Cambridge Research Center. The first rocket, AM6.31, a Nike-Cajun, fired on October 20, 1956, reached 70 mi. An Aerobee, AM2.21, launched three days later, reached 90 mi. Alphatron pressures gages were used to obtain the primary data. The Alphatron derives its name from the fact that it uses a polonium source of alpha particles to ionize the residual air between a pair of collecting electrodes. A gage mounted at the nose tip of the rocket measured stagnation pressure. Gages on the side of the nose cone measured cone-wall pressure. Pressure at the tip of the nose cone is, of course, much greater than on the side because of the high speed of the rocket. The ratio of these two pressures is theoretically related to the Mach number. But the Mach number is the ratio of the velocity of the rocket to the velocity of sound in the surrounding atmosphere. Since the velocity of sound increases with temperature, the Mach number is thermo-dependent. The relationship is expressed by

$$M = v\sqrt{\mu/rRT} \tag{1}$$

where M is the Mach number, v is the speed of the rocket, μ is the mean molecular weight, r is the ratio of specific heats, R is the universal gas constant, and T is the absolute air temperature. The square-root term is simply the velocity of sound. M and v are measured by the experiment, μ is known approximately from independent data and rR is a known constant. The experiment therefore makes it possible to calculate T. The results are valid up to about 100 km.

The Mach number of the flying rocket can be determined independently from the angle of flow of air over the surface of the nose cone when the rocket flies at an angle to the air stream. Theory also relates the ambient pressure to the pressure measured on the side of the rocket and the Mach number. Data analyses of the two University of Michigan firings at Fort Churchill are still incomplete.

An Aerobee-Hi rocket, NN3.12, fired on November 17, 1956, at Fort Churchill was instrumented by H. E. LaGow of the Rocket Sonde Branch, of the Naval Research Laboratory (NRL) with a variety of pressure gages. The NRL methods are similar in many respects to those described above. Bellows gages are used at low altitudes and Pirani and Phillips gages at successively higher levels of the atmosphere. Air density is derived in the NRL method from the stagnation pressure measured at the nose tip by reference to the Rayleigh formula which is valid below 100 km. At higher altitudes, the NRL experiment makes use of gages mounted on the side of the rocket. Above 100 km the rocket is tipped over so that it is moving sidewise and then rolled by means of small peripheral jets. Each gage alternately looks 'into the wind' and

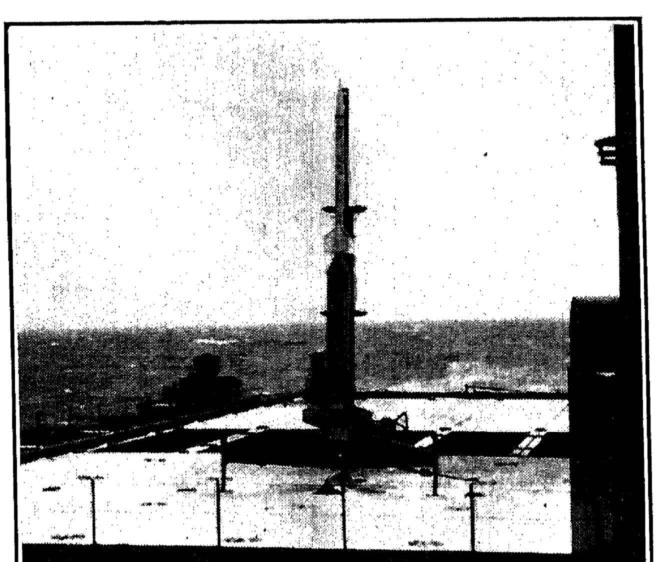

FIG. 3 — Nike-Cajun on deck of USS *Rushmore*, LSD–14

'away from the wind' thereby producing a pressure modulation with the period of the roll of the rocket. According to kinetic theory the ambient air density is directly related to the amplitude of the pressure modulation and the speed of the rocket. The rocket reached an altitude of 130 miles and good data were obtained throughout the flight.

Included in all NRL Aerobees flown at Fort Churchill during the daytime, is an extension section prepared by the Optics Division of NRL. These extensions contain two photon counters, one which measures soft x-rays and the other the ultraviolet Lyman alpha line from the Sun. As the radiation penetrates the atmosphere it is attenuated in a characteristic fashion determined by the absorption coefficient of the air and its density. Assuming that the solar flux is steady, the variation in intensity at the rocket as it rises through the air provides a direct measurement of total air mass above the rocket at any altitude. From such data, the density versus altitude is obtained. The x-ray wave lengths are absorbed in E region, 100–130 km, the Lyman α in D region, 75–90 km. The detectors are mounted with their windows flush with the skin of the rocket. As the rocket rolls, they see the Sun once each roll period. Aerobee NN3.12 rolled so slowly that each detector got barely two or three looks at the Sun in the appropriate altitude ranges. The data were therefore insufficient to deduce a density curve.

Aerobee SM1.01, fired during the night of November 12, 1956, at Fort Churchill was instrumented by University of Michigan for the U. S. Army Signal Engineering Laboratories with the 'exploding grenade' experiment. This experiment is essentially a sound ranging method of determining temperatures and winds. If the velocity v of sound can be measured, the temperature T can be derived from the relationship

$$v^2 = rRT/\mu \qquad (2)$$

The quantities are the same as defined in (1). As the rocket rose to a height of 42 mi, 18 grenades were ejected in a predetermined timed sequence and exploded. The explosions were photographed from the ground and timed by telemetered signals from the rocket. Arrivals of the sounds of the explosions at each of several ground stations were also accurately timed. The photographs located the positions of the explosions against the star background. From the position of the bursts and the transit times to ground, it is possible to deduce the speed of sound at various levels and the distribution of atmospheric winds.

According to W. G. Stroud of Signal Engineering Laboratories, the data from this first firing have been reduced so that 15 values of temperature and winds have been obtained. The peak temperature at 50 km was about the same as at White Sands, N.M., that is, 276°K. The winds were moderate from the west, again as at WSPG. At the lower altitudes, temperatures were within 3°K of previous balloon values.

Solar radiation measurements—The Sun radiates a broad spectrum of wave lengths from cosmic rays to radio waves. We see visually only the narrow wave length range from 4000 to 7500 Angstroms. With the aid of ultraviolet or infrared sensitive detectors and radio receivers we can measure a wider spectrum at sea level in two broad atmospheric windows, the optical window from 2900 A to 30,000 A and the radio window from one centimeter to about 40 m. Outside these windows the air above is almost totally opaque.

Early attempts to see beyond 2900 A in the ultraviolet were made from mountain top observatories and from balloons. In 1934, a spectrograph was flown to 30 km in a balloon but even that height was not adequate. Not until October 10, 1946, when a spectrograph was carried aloft in a V-2 rocket, was our knowledge of the solar spectrum extended into the region of ultraviolet that is absorbed by ozone before it can reach ground. Since then many successful spectrograms have been obtained, the best one reaching to 977 A.

To study the interaction of solar radiation with the ionosphere, it is necessary to fly spectrographs or photoelectric detectors to altitudes above 50 mi. Over the past ten years, photon counters flown in rockets have revealed a steady flux of solar x-rays that are absorbed in E and F regions. In the D region a characteristic wave length of 1215.7 A is always observed in the far ultraviolet. This is the strongest emission line of the atomic hydrogen spectrum, known as Lyman alpha, and it alone is responsible for ionization of the D region when the Sun is quiet.

In integrated white light, the Sun appears to be a stable star. Looked at in various discrete

wave lengths, however, the Sun is a variable star. The term solar activity includes a variety of long- and short-lived transient phenomena, such as sunspots, plages, dark filaments, faculae, prominences, flares, and coronal regions that are bright in red, green, and yellow line emissions. All these phenomena follow the general trend of sunspot number and occur in close proximity to sunspot groups. The ionizing radiations may come from the entire area of the disk, from centers of activity, and from the corona. In the case of flares there is a unique correlation.

The catastrophic magnitude of a solar flare can best be appreciated when it is viewed in the red-light characteristic of excited hydrogen atoms in the chromosphere. In a matter of minutes, a local region of the solar surface may increase tenfold in brightness and the flash spreads over hundreds of millions of square miles. Simultaneously with the flash, the ionosphere becomes so dense in the D region that broadcast frequencies are completely absorbed and communications disrupted (Fig. 4). This condition is known as radio fadeout. Reception does not return to normal until the flare disappears, which may take half an hour to several hours depending on the size of the flare.

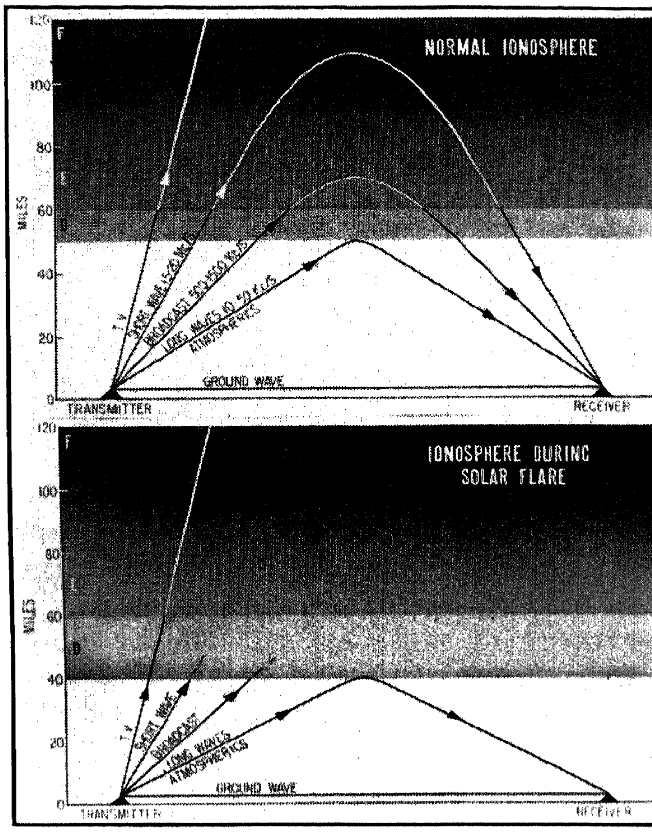

FIG. 4 — Reflection of radio signals by the ionosphere; frequencies above 20 mc escape ionosphere completely; broadcast frequencies and short waves are reflected from E and F regions; during a flare, D region ionization increases and the base of the ionosphere is lowered; short wave and broadcast frequencies fade out, but atmospherics are enhanced

In spite of the wealth of ground-level observations of flares at astronomical observatories we still know very little about the processes that produce them or how the flare energy is partitioned between ultraviolet, x-rays, and even cosmic rays. To study the emission of a flare it would appear to be only necessary to fire a rocket during a flare. Flares, however, occur infrequently, very rarely during the minimum period of a solar cycle and perhaps one interesting flare every 50 hours near sunspot maximum. To fire a large rocket during a flare from an established proving ground is very difficult, since it must be in the launching tower, fully fueled and ready to launch at a moment's notice any time during the day. Small solid-propellant rockets fired at sea or from an isolated island location are much more appropriate to a flare experiment.

Techniques of small rocketry and miniaturized electronics have now progressed to the point where rockets instrumented with standardized flight packages may be flown on short notice from temporary launching sites on land or from shipboard. This makes it possible to synchronize firings with astronomical events such as solar flares. A program of small rocket experiments is planned for the measurement of flare x-rays and ultraviolet during the IGY by members of the Optics Division of NRL under the author's direction. During pre-IGY tests ten Rockoons, NN5.27 to NN5.36 inclusive, were fired at sea about 300 mi southwest of San Diego.

The Rockoons were chosen as the only solution available at the time to the problems of restricted range scheduling. The ocean area southwest of San Diego was chosen because it was remote from established air and shipping lanes and also sufficiently remote from the radio disturbances of the auroral zones so that local radio disturbances could be correlated with solar flares. The operating area was also within dependable radio-reception range of the solar observatories at Sacramento Peak, N.M., and at Climax, Colorado.

In a Rockoon launching, the balloon and its rocket load ascend to an altitude of 80,000 ft at

approximately 1000 ft/min. The plan was to float the combination at this altitude until a flare was detected by radio or optical means, at which time a radio relay would be used to activate the instrumentation and fire the rocket. During the experiments the U.S.S. *Colonial,* LSD-18, served as the launching vessel, while the U.S.S. *Perkins,* a destroyer, tracked the balloon with its radar.

The Deacon rocket was suspended from the balloon by 100 ft of nylon line, terminating in a steel ring which mated with a hook attached to the rocket motor. When the rocket was fired the hook slipped out of the ring and the rocket tore through the balloon, whose polyethylene envelope offered little resistance to the rocket. Within a minute and a half after firing, the spent rocket and its payload reached an altitude of 60 to 70 mi. For a period of about three minutes near peak of the flight data on the strength of Lyman alpha and x rays were telemetered back to the ship.

The instrumentation section of each Rockoon is divided into three major subassemblies: a telemetering deck, power deck, and electronics deck. The major components in each of the four data channels of the FM-FM telemeter are plug-in units, as are the detectors in the shell. The latter include two aspect photocells, a Lyman-alpha ion chamber, a soft x-ray photon counter and a hard x-ray scintillation counter. Figure 5 illustrates the balloon and its load just after launching. The load includes, besides the rocket: a time-and-pressure release mechanism to cut down the rocket if the rocket motor fails to start; a radiosonde to provide continuous pressure altitude data; three radar corner reflectors for tracking; and finally a command receiver to fire the rocket. Figure 6 is an artist's sketch of the experiment.

Rockoons were launched in the mornings of ten days between July 16 and July 29. Only one small flare was detected during the expedition but the rocket measurements revealed an x-ray flash extending the spectrum to nearly 3 A and persisting well after Lyman-alpha had decayed to normal. At its short wave length limit it resembled the emission of a four-million degree thermal source. Although the flare was something between Class 1 and a subflare, the x-ray intensity theoretically was sufficient to produce a substantial increase of D-region density between 75 and 85 km.

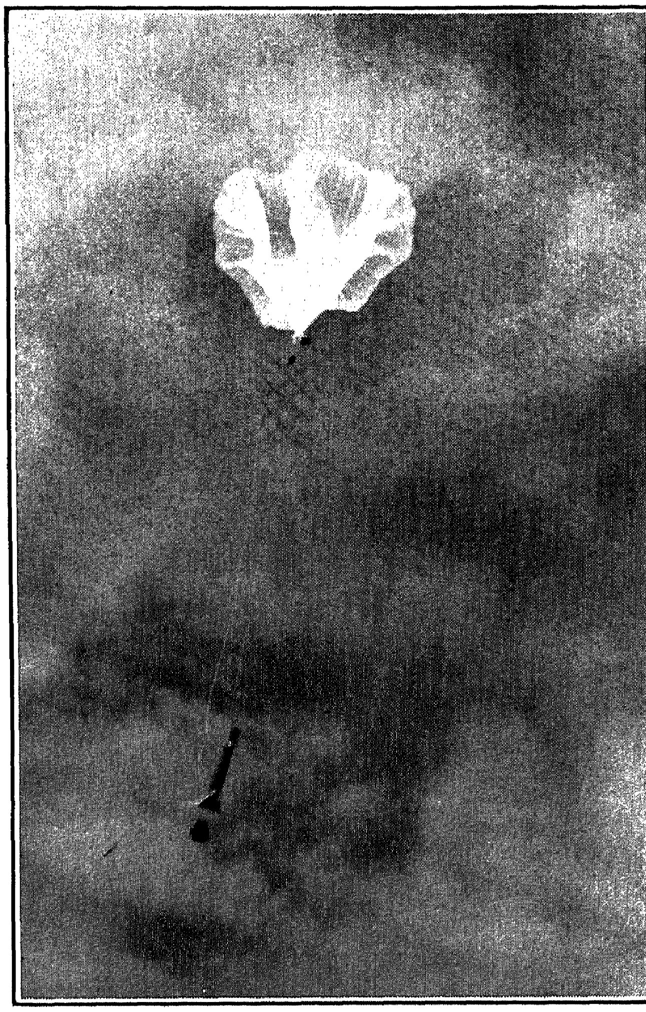

FIG. 5 — Rockoon just after launching from shipboard

Many lessons were learned from the pre-IGY flare experiment. The scientific results were exciting but the Rockoon technique was inefficient. On days when no flare was observed, the rockets had to be fired before they drifted out of range. The logistic support was too expensive an operation to continue over a long period of time. For the IGY, therefore, the program has been altered to utilize the Nike-Deacon combination on San Nicolas Island, part of the Point Mugu, California, facility. Fourteen rockets have been prepared and excellent communications have been established with Mount Wilson, Sacramento Peak, and Climax. The first shoot is tentatively scheduled for July 1, 1957 to test the over-all plan of operations and to provide a normal background for comparison with flare conditions. The remaining 13 launchings will be reserved for SID producing flares. In the event of a very large flare, more than one shoot will be attempted during the course of the flare.

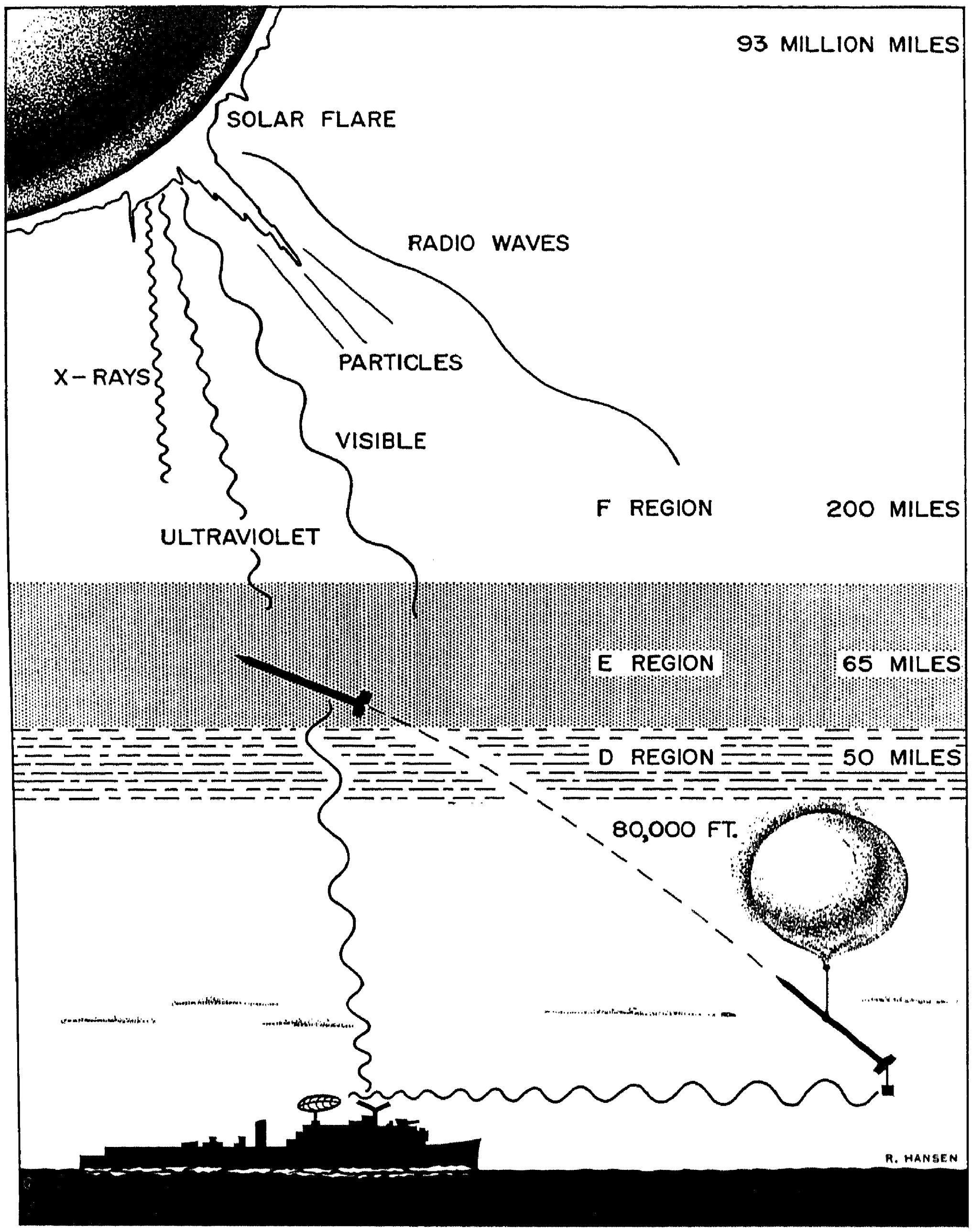

FIG. 6 — Artist's sketch of Rockoon solar-flare experiment

The ionosphere—Practically all our knowledge of the ionosphere prior to rocket measurements was based on radio soundings. A pulse of radio waves entering a cloud of electrons is reflected when the density of electrons reaches a critical value proportional to the square of the radio frequency. The time required for the pulse to travel to the ionosphere and back to ground is a measure of the height of the reflecting region. At certain critical frequencies there appear abrupt discontinuities in reflection heights, as though the electron density was distributed in several well defined layers. These layers are named E, F_1, and F_2. In the lowest region, called D, the electron density is too small to reflect frequencies in the megacycle range. The lower ionosphere normally acts as a partial absorber for these broadcast-band waves and as a good reflector for very long waves such as the atmospherics or static generated by thunderstorms (Fig. 4).

Our present rocket picture of the ionosphere is a continuum of ionization without discretely separated layers. F_1 shows up as just a small bump in the curve of electron density distribution and the entire ionosphere is lower than appears from the simplest analysis of radio soundings. When we consider the solar spectrum

responsible for the ionization of a static atmosphere, it seems very unlikely that the ionosphere could have abruptly bounded stratifications.

A method of determining electron density directly was developed by J. C. Seddon of the Rocke Sonde Branch, NRL. The method utilizes relationships between refractive index, which depends on electron density, and the Doppler shifts of two signals broadcast from the rocket to the ground. Two harmonically related CW frequencies are radiated from the rocket to two stations on the ground, about six miles apart and approximately in the plane of the rocket trajectory. The frequencies used are 7.754 mc/s and its sixth harmonic 46.524 mc/s. The higher frequency suffers almost no retardation in E region and serves as a reference frequency against which the lower frequency is compared. At the ground station the lower frequency is multiplied by a factor of 6 and combined with the high frequency to produce a beat signal. If the position and velocity of the rocket is known the measured beat frequency contains the information from which the refractive index at that position can be determined. Figure 7 illustrates the relationship of the two frequencies and the effect of the ionosphere on the lower one.

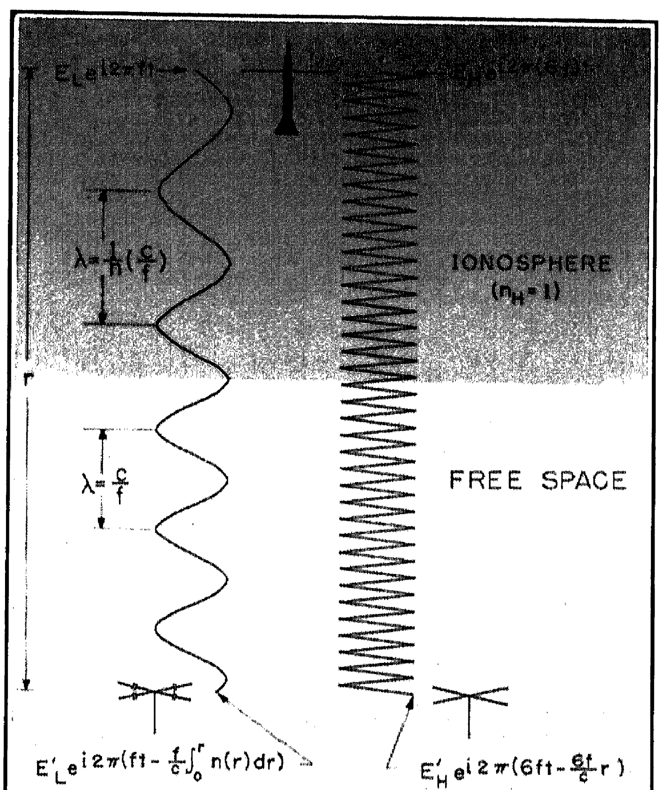

FIG. 7 — Propagation experiment; signals in free space are harmonically related; high frequency is sixth harmonic of lower frequency; in the ionosphere the high frequency is unaffected, but the low frequency is increased in wave length

An interesting feature of the instrumentation of Aerobee-Hi, NN3.037, prepared by the Rocket Sonde Branch of NRL, under the direction of J. E. Jackson, is the dipole antenna that radiates the two frequencies. The dipole consists of two whips, 14 ft long, extended perpendicular to the axis of the rocket. During the early part of the rocket flight, the whips are held retracted against the skin of the rocket to keep them out of the air stream. Above 60 km, the air drag is negligible and the antenna is automatically extended. The rocket was launched on November 12, 1956, and reached 80 mi. This was a comparatively poor rocket performance but the experiment worked well and the data are being analyzed.

Nike-Cajun OB6.00 was instrumented by the Ballistic Research Laboratories under the direction of W. W. Berning for the study of charge density in the upper atmosphere. The method used is based on DOVAP (Doppler velocity and position). In the DOVAP system, two RF signals are transmitted from one ground station to another, one signal directly, the other by way of the rocket. The radiation picked up by the rocket in flight is rebroadcast to the ground. If the rocket is rising the rebroadcast signal is lower in frequency because of the Doppler effect. At the peak of the flight the rebroadcast signal is unaltered in frequency, and on the downward leg the frequency is increased. The signal from the rocket is received at three or more ground stations and is beat against the directly received ground wave. The resulting beat frequency is proportional to the rocket velocity in the plane including the transmitter, rocket, and receiver. Integration of the Doppler frequency as a function of time gives, when multiplied by the wave length, the distance from transmitter to rocket to receiver at any time. All of the foregoing is true if propagation takes place in vacuum. The presence of an electron density in the radiation path introduces a retardation which affects the DOVAP position computation by a measurable amount. Therefore, if position at high altitudes can be computed from low altitude trajectory data with high accuracy, the discrepancy with DOVAP position can be used to obtain electron density. The Nike-Cajun firing was primarily a test of

the suitability of the rocket for such measurements.

Atmospheric composition—Under the influence of solar ultraviolet radiation O_2 is dissociated rapidly above 100 km, but dissociation never reaches completion even in F_2 region. The existence of O_2 at such high altitudes is dependent on the intensity of solar radiation, diffusion, and turbulent mixing. Experimentally the O_2 concentration has been determined by observing the transmission of 1500 A radiation from the Sun to a photon counter in the rocket. Such a measurement is feasible because O_2 absorbs this wave length strongly, whereas no other major atmospheric constituent absorbs it appreciably. Unfortunately, similar determinations of other major constituents is not feasible spectroscopically.

For several years NRL has been conducting experiments utilizing the Bennett radio-frequency mass spectrometer to determine the neutral gas and ion composition at high altitudes. Aerobee-Hi NN3.17 was flown at night at Ft. Churchill on November 20, 1956, instrumented by Edith Meadows and C. Y. Johnson of the NRL Rocket Sonde Branch with three RF spectrometers. One RF spectrometer was mounted axially near the tip of the nose cone to measure neutral gases. At high altitude the nose tip was ejected, exposing the spectrometer to the atmosphere. An electrically operated pyrotechnic squibb actuated an 'explosive hammer' that broke a glass tubulation sealing the intake of the spectrometer at the same time that the forward section of the nose cone was ejected by a spring. The spectrometer starts to function when the pressure drops below 4×10^{-4} mm Hg. In operation, the spectrum between mass numbers 50 and 6 was swept electrontically once every $1\frac{1}{4}$ seconds with a resolution of one part in forty, leaving an uncertainty of about one atomic mass unit throughout the sweep range. The neutral gas spectrometer carried its own internal means of ionizing the ambient atmospheric gases that entered it. Two additional spectrometers were carried in the nose cone, but mounted perpendicular to the axis. These spectrometers were employed without ionizing sources and simply measured the atmospheric ions that diffused into their collecting fields.

Changes in the ratio of argon to molecular nitrogen, measured by the neutral gas spectrometer indicated that diffusive separation of the atmospheric gases started between 100 and 110 km. As the rocket rose, peaks of mass number 16 and 30 became increasingly important components of the spectra. At 224 km, the highest altitude at which a neutral gas spectrum was obtained, amplitudes of masses 16 (O), 28 (N_2), 30 (NO), and 32 (O_2) differed from each other by less than a factor of 3. The amplitude of 32 was undoubtedly enhanced by the recombination of O atoms on the walls of the inlet tube. Spectra were obtained from the positive ion spectrometer in the mass range 53 to 6 AMU for 375 sec while the rocket was above 90 km. Mass 30 was the first positive ion detected and it remained in the spectra throughout the flight. Positive ions of mass 32 and 16 subsequently appeared. The mass 16 positive ion became the predominant ion with increasing altitude. Two minor positive ions of mass 28 and 18 were detected during the flight. A possible identification of these ions is: 32, O_2^+; 30, NO^+; 28, N_2^+; 18, H_2O^+; 16, O^+. Above 170 km there is indirect evidence of a positive ion with relatively large abundance at mass 63 ± 2 AMU. A spectral peak in the region of mass 46 (NO_2^-) was detected by the negative ion spectrometer. Nitric acid, one of the rocket's propellants, might have contributed to some of these ion peaks, although data from the neutral gas spectrometer at the nose of the rocket indicated that the rocket was 'clean.'

Auroral particles and ultraviolet—Auroral displays are well correlated with solar activity. In contrast to the prompt ionospheric effects of electromagnetic radiations in a solar flare, the auroral disturbances are delayed one or two days. Such delays are associated with the travel time of corpuscular streams from Sun to Earth. Spectroscopic evidence, in the form of broad hydrogen lines in the auroral spectrum, indicates protons as the source of excitation. The fast incoming protons radiate the hydrogen emission lines after capturing electrons as they are slowed down in the upper atmosphere. Rocket measurements thus far have been designed primarily to identify the energetic particles or radiations in the auroral zone. Virtually all the information available is based on Rockoon flights by Van Allen and his colleagues of State University of Iowa. Their measurements in the auroral zone have revealed a soft radiation at altitude of 40–70 km which exhibits the charac-

teristics of x-rays in the 10–100 kev range. Van Allen concludes that the x-rays are associated with primary auroral radiations but are not themselves primary in nature. If the x-rays are produced by the *Bremsstrahlung* of primary electrons that are stopped at about 90 km, the observed intensities are reasonably consistent with the visible energy content of the aurora.

During the IGY, attempts will be made to identify the auroral radiations by means of Geiger counters, proportional counters, scintillation counters and electrostatic energy analyzers. Aerobee-Hi rocket NN3.02 was instrumented by L. E. Meredith and J. P. Heppner of the Rocket Sonde Branch of NRL for such auroral measurements at Ft. Churchill, but the rocket exploded while being held in the tower for an auroral display. Each NRL night-time Aerobee at Ft. Churchill will carry a small additional experiment consisting of two photon counters, one sensitive to the ultraviolet band, 1100–1350 A, the other sensitive to the band 1220–1350 A. The latter band covers a region of strong air fluorescence under particle excitation. According to theory the Lyman alpha intensity arising from protons in the aurora should be very intense.

Photon counter instrumentation was flown by E. T. Byram of the Optics Division, NRL, in Ft. Churchill Aerobee NN3.17. Preliminary inspection of the data shows that the Lyman alpha intensity was comparable to that obtained at WSPG in an earlier measurement, but that the intensity in the 1220–1350 A band was about ten times as high as at WSPG. The rocket was flown in an overcast and visual observation of the aurora was not possible.

Magnetic fields—Direct information about the

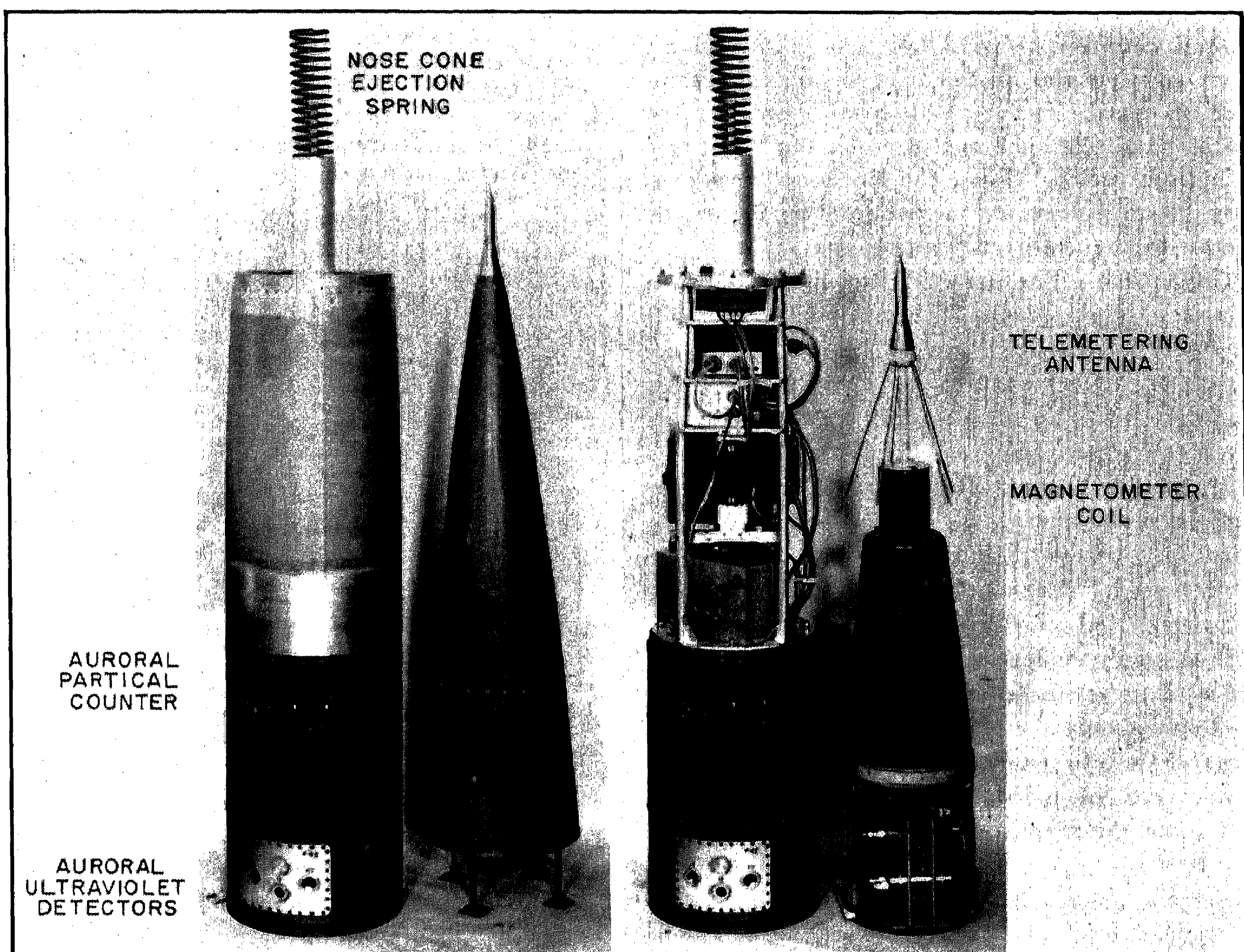

FIG. 8 — Magnetometer, auroral particle counters, and auroral radiation detectors in Aerobee-Hi nose cone; magnetometer structural supports are nonmetallic; at peak of flight magnetometer is ejected to free it of influence of rocket; middle section contains auroral ultraviolet detectors

altitude and magnitude of an ionospheric current system can be obtained from the observation of a discontinuity in the Earth's field as the rocket passes through the current sheet. One of the most promising new instruments for magnetic measurements from rockets is the proton precession magnetometer. The ill-fated NRL Aerobee NN3.02 was instrumented with a magnetometer in addition to auroral radiation detectors. Figure 8 illustrates the arrangement of instrumentation. On the right-hand side is the magnetometer section. The portion of the nose cone that covers the magnetometer coil is made of plastic, since any conductive material will distort the field. At the peak of the flight the magnetometer section is separated from the rocket by the helical ejection spring, and carries along its own telemetering antenna and circuitry. The instrumentation which remains with the rocket includes the auroral particle counters and the ultraviolet photon counters. Van Allen and his associates have adapted the proton precession magnetometer to small rockets and have demonstrated the feasibility of such measurements in the three-inch Loki rocket. Using the Rockoon technique, they plan numerous measurements from the Arctic to the Antarctic during the IGY.

Conclusion—The pre-IGY firings represent a sampling of the kinds of experiments that will be undertaken during the IGY. It is characteristic of rocket experiments that data are accumulated in a matter of minutes, but analysis often takes many months. The complete stories of the pre-IGY experiments are not yet available and several years may elapse before all the scientific yield of the forthcoming IGY Rocket Program is derived from the telemetering records.

It is amply evident from even the partial program of experiments described above that the IGY is not only the climax of the first decade of research with rockets, but the inauguration of a new era of high-altitude explorations. We now have the means of launching rockets from ships and from stations scattered over the world from the Arctic to the Antarctic. Small solid-propellant rockets make synoptic measurements comparatively inexpensive and permit close synchronization of measurements with solar activity. At the same time, evidence from related fields of science reveal exciting new phenomena of the atmosphere at heights extending to several thousand miles. For the attack on these new problems we look forward to another order of magnitude gain in altitude capabilities of multistage rockets and to the use of earth satellites.

References

Bartman, F. L., L. W. Chaney, L. M. Jones, and V. C. Lin, Upper-air density and temperature by the falling-sphere method, *J. App. Phys.*, **27**, 706–712, 1956.

Byram, E. T., T. A. Chubb, and H. Friedman, Solar x-ray spectrum and density of the upper atmosphere, *J. Geophys. Res.*, **61**, 251–263, 1956.

Chubb, T. A., H. Friedman, R. A. Kreplin, and J. E. Kupperian, Jr., Rocket observations of x-ray emission in a solar flare, *Nature*, **179**, 861–862, 1957.

Jackson, J. E., J. A. Kane, and J. C. Seddon, Ionosphere electron density measurements with the Navy Aerobee-Hi rocket, *J. Geophys. Res.*, **61**, 749–751, 1956.

Johnson, F. S., J. D. Pucell, R. Tousey, and N. Wilson, The ultraviolet spectrum of the Sun, *Rocket exploration of the upper atmosphere*, pp. 279–288, Pergamon Press, 1954.

Horowitz, R., and H. E. La Gow, Upper-air pressure and density measurements from 90 to 220 km with the Viking 7 Rocket, *J. Geophys. Res.*, **62**, 57–78, 1957.

Sicinsky, H. S., N. W. Spencer, and W. G. Dow, Rocket measurements of upper-atmosphere ambient temperature and pressure in the 30- to 75-km region, *J. App. Phys.*, **25**, 161–168, 1954.

Stroud, W. G., W. Nordberg, and J. R. Walsh, Atmospheric temperatures and winds between 30 and 80 km, *J. Geophys. Res.*, **61**, 45–56, 1956.

Townsend, J. W., E. B. Meadows, and E. C. Pressly, A mass spectrometric study of the upper atmosphere, *Rocket exploration of the upper atmosphere*, pp. 169–188, Pergamon Press, 1954.

Van Allen, J. A., Direct detection of auroral radiation with rocket equipment, *Proc. Nat. Acad. Sciences*, **43**, 57–62, 1957.

Naval Research Laboratory, Washington 25, D. C.

The Vanguard Satellite Launching Vehicle — Placing the Satellite in Orbit

John P. Hagen

Introduction—The Vanguard satellite launching vehicle will be called upon to establish artificial satellites in orbits around the Earth during the International Geophysical Year. Succeeding problems are to prove that it is indeed there and to perform scientific experiments using the satellite. It was early decided that the orbit must lie outside the absorbing atmosphere to make possible measures of the electromagnetic and corpuscular radiation coming in from outer space and to determine their geophysical effects. It was also decided that the orbit should be sufficiently within our atmosphere to make possible studies of the atmosphere itself. The design of the launching vehicle evolved from a consideration of the minimum requirements imposed by the vehicle mission, the current status of the art in rocketry, the current status of guidance and rocket instrumentation, and the logistic problems associated with the launching of a rocket of the magnitude involved.

The physical characteristics of the satellite package were selected as follows. It would be spherical in shape initially, having a diameter of 20 inches. It would have a gross weight of $21\frac{1}{2}$ pounds and it would be capable of separation from the final stage of the vehicle. The orbital requirements were: (a) a nominal orbital altitude of 300 miles; (b) an initial perigee altitude of not less than 200 miles; (c) an apogee altitude of not greater than 1400 miles; (d) an inclination of the orbit to the equator of $40° \pm 5°$; and (e) the launching site is to be the Air Force test launching station at Cape Canaveral, Florida.

Orbits—The principal demands on the performance of the launching vehicle are determined by the characteristics of the Earth's gravitational field and its atmosphere. Circular orbits lying only a small fraction of the Earth's radius above the Earth's surface require an orbital speed of about 25,000 ft/sec. As the orbits get larger the required speeds go down until, at the Moon's distance, the required speed is only about 3000 ft/sec. However, while the kinetic energy is thus lower in the larger orbit, the total energy is greater because of the large increase in potential energy require to remove the body far from the Earth. In the case in hand then, the launching vehicle must impart sufficient potential energy to the satellite to lift it some 300 mi above the Earth and then sufficient kinetic energy to give it the required speed to maintain it in its orbit.

Atmospheric drag on the satellite is slight. Nevertheless, its accumulative effect over the relatively long flight time of the satellite results in a significant decrease in the satellite's energy, and a corresponding decrease in the length of the semi-major axis of the orbit. Ultimately, when the satellite has descended far enough into the lower, denser atmosphere, aerodynamic effects will cause it to heat up and to become, in effect, a kind of artificial meteor. The satellite's lifetime increases as the air density in the neighborhood of the initial orbit decreases. Air density falls off roughly exponentially as altitude increases (Fig. 1).

The lifetime of the satellite should be at least a fortnight, in order to allow adequate time for conducting significant geophysical and astrophysical researches. A longer lifetime, on the order of a year, would expand the potential scope of the satellite's geophysical usefulness. It has been estimated that an initial circular orbit at the height of about 200 mi is required in order to achieve an adequate lifetime. The desired minimum initial perigee height of the Vanguard satellite was taken to be 200 mi.

The character of the orbit is determined by the satellite's position and velocity vectors when it is projected into its orbit; that is, when it receives its last impetus from the final stage of the rocket launching vehicle. If the speed is exactly that required for a circular orbit beginning at the projection height and if the velocity vector is truly horizontal, the orbit will be circular. If either condition is not fulfilled, the orbit will be elliptical. Actually, it is highly unlikely that either condition will be met. If, for example, the projection velocity is less than that required for a circular orbit beginning

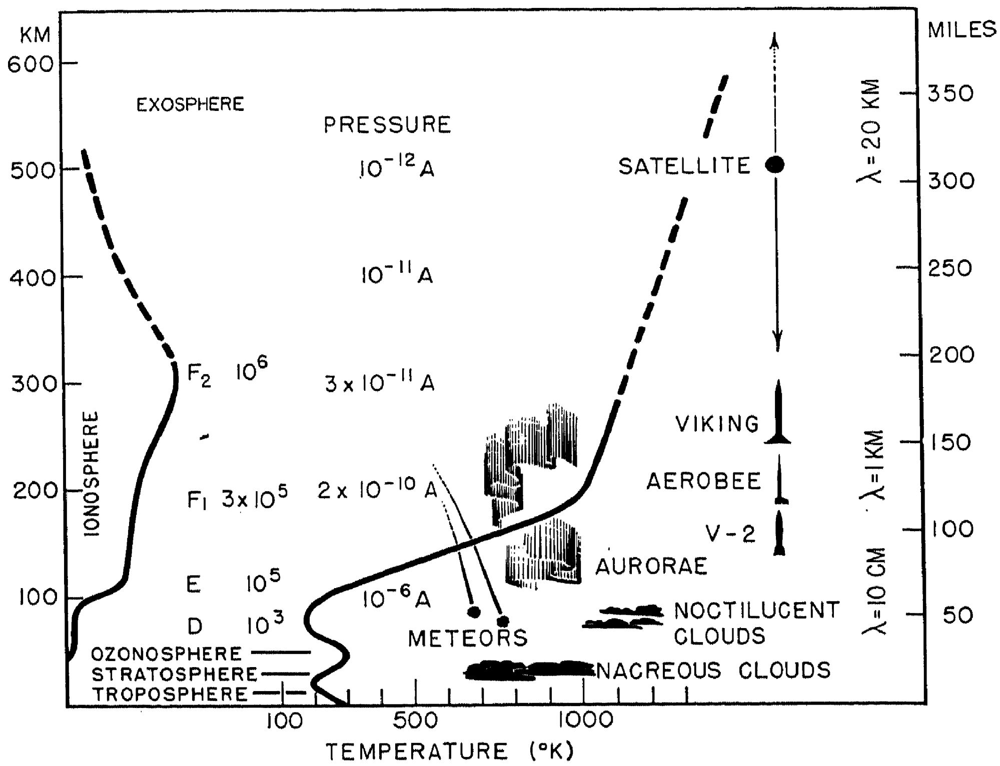

FIG. 1 — Schematic cross section of the atmosphere

at the projection height, the orbit will be a subcircular ellipse and its perigee, or point of closest approach to the Earth, will be less than the projection height. This problem is approached by designing an excess velocity capability into the launching-vehicle system so that, allowing for normal errors, the satellite will still have an adequate velocity. If at projection the horizontal velocity exceeds that required for a circular orbit, the orbit will be elliptical and its apogee, or point of greatest distance from the Earth, will be greater than the projection height (Fig. 2).

If the velocity vector is directed slightly downward at projection, the satellite will dip into the lower atmosphere before rising again. Hence the perigee height will be lower than the projection height. Aiming high is of no real help, however. For example, if two satellites are projected at the same small angle to the horizontal, one downward and the other upward, the resulting orbits will be similar and will be symmetrically located with respect to the projection point (Fig. 3). In either case the perigee height will be the same. In the latter case, however, it will occur a little later, after nearly a

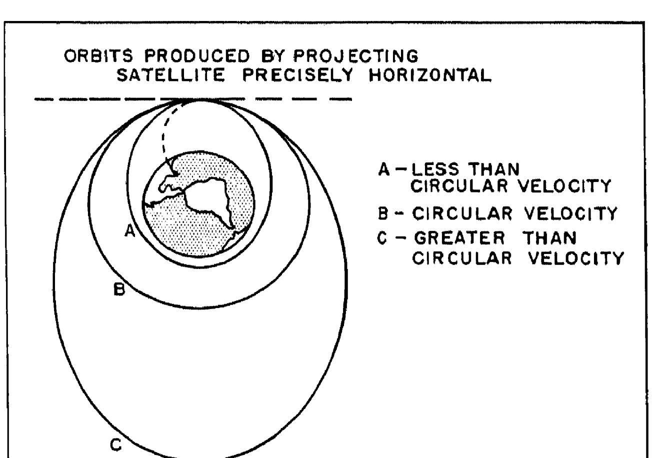

FIG. 2 — Satellite orbit possibilities depending on projection velocity

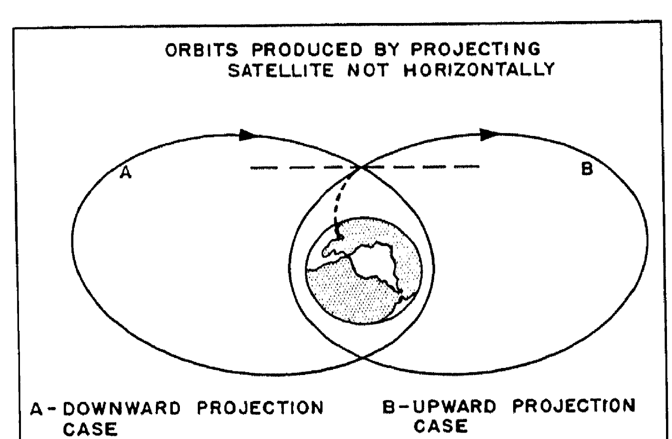

FIG. 3 — Satellite orbit possibilities depending on projection angle

whole revolution has been completed. Practically speaking, then, velocity vector deviations either upward or downward are equally undesirable; hence, an accurate control system for aiming the third-stage velocity is essential.

In order to allow for the fact that the projection velocity vector might not be truly horizontal, the projection altitude should be higher than 200 mi. A projection altitude of about 300 mi appears to be consistent with the various requirements and characteristics associated with the satellite launching vehicle. The projection altitude and perigee limitations are shown better in Figure 4. This figure is drawn for a launching height of 300 mi, for the orbit limitations of 200-mi perigee and 1400-mi apogee. If there were no angular errors in launching, the velocity could lie anywhere between 99 and 105 pct of the circular velocity and still keep the orbit within the limits set. If there are angular errors, the allowable error in launching angle rapidly increases as the launching speed increases, so that when the launching speed is five per cent above the circular speed an error of approximately four degrees in either direction can be tolerated. The minimum horizontal velocity for a circular orbit at 300 mi altitude represented by the 100 pct index of Figure 4 is 25,034 ft/per sec. The launching vehicle is being designed with a capability of establishing a launching speed considerably in excess of this number to

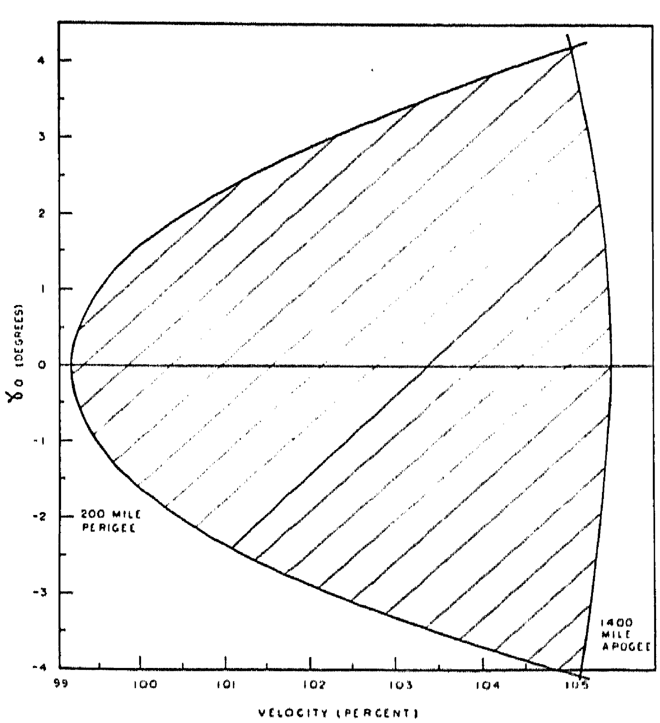

FIG. 4 — Satellite orbit tolerance diagram

allow for shortcomings in the performance of the various components in the vehicle.

The two major perturbing effects on the orbit are air density and the non-uniform shape of the Earth. Each acts, of course, in a different way: one tends to destroy the orbit by slowly removing energy, the other simply tends to modify the plane of the orbit.

The density of the air above 200 mi altitude is not accurately known, but by extrapolating from rocket measurements of density, we can estimate its magnitude, certainly within a factor of 10. These estimates lead to the conclusion that the rate at which the drag affects the motion of the satellite will be such as to permit a lifetime in excess of a few weeks. As drag removes energy from the orbit, the first effect will be to reduce the apogee distance with little effect on the perigee. This can be observed as a slow change in the height of the satellite as it passes overhead but will be more accurately observed and measured through the change in the period of the satellite. The second perturbation is due to the equatorial bulge of the Earth, which causes the plane of the orbit to precess and also causes the position of perigee to slowly move around the orbit. These effects are greater here than in any other known astronomical case since here the satellite is so close to the primary attracting body. Its very closeness makes the gravitational effect of the bulge proportionately larger than the attraction of the remainder of the spheroid. There is a component of this attraction which is at right angles to the plane of the orbit and this component tends to cause the plane to precess, as a gyroscope does.

The planned inclination of the plane of the orbit to the plane of the Earth's equator is $40° \pm 5°$. This inclination was chosen as a compromise among several factors: scientific, range safety, and location of launching facilities. The launching facility chosen was the Air Force test launching station at Cape Canaveral, Florida, at a latitude of 28° 30′ north. The plane of the orbit must contain the center of the Earth and hence the minimum inclination of the orbit is the latitude of place of launch. Greater inclination than this can be obtained by choosing a launching azimuth which is either to the north or to the south of the due east direction. Geographical considerations make it desirable to incline the launch trajectory to the south of east but at the same time limit the maximum

inclination to that which results in a total inclination somewhat in excess of 35°. It is advantageous to launch the satellite as nearly toward the east as is possible in order to take advantage of the rotation of the Earth about its axis. The velocity gained due to this effect is on the order of 1300 ft/sec at this latitude and contributes directly to the velocity required to maintain the satellite in its orbit.

The limiting orbit, even though the ratio of perigee to apogee is 200 to 1400, is very slightly elliptical. Once the vehicle has left the stand and has put the satellite into an orbit, the satellite is free of the rotation of the Earth on its axis. The plane of the orbit will remain relatively fixed and the Earth therefore will turn under it. On successive passages it will cross the equator further and further to the west. The expected period for the satellite is about 100 minutes, so that there will be approximately 16 circuits of the Earth during one day. In an orbit whose inclination is 35° to the equator, the sub-satellite point criss-crosses the area of the Earth bounded by N latitude 35° and S latitude 35°; the tracking stations must, therefore, be located in these regions.

Time in sunlight—It is important to consider and attempt to control the time the satellite would stay in sunlight. It is the time in sunlight which is the controlling factor in the heat

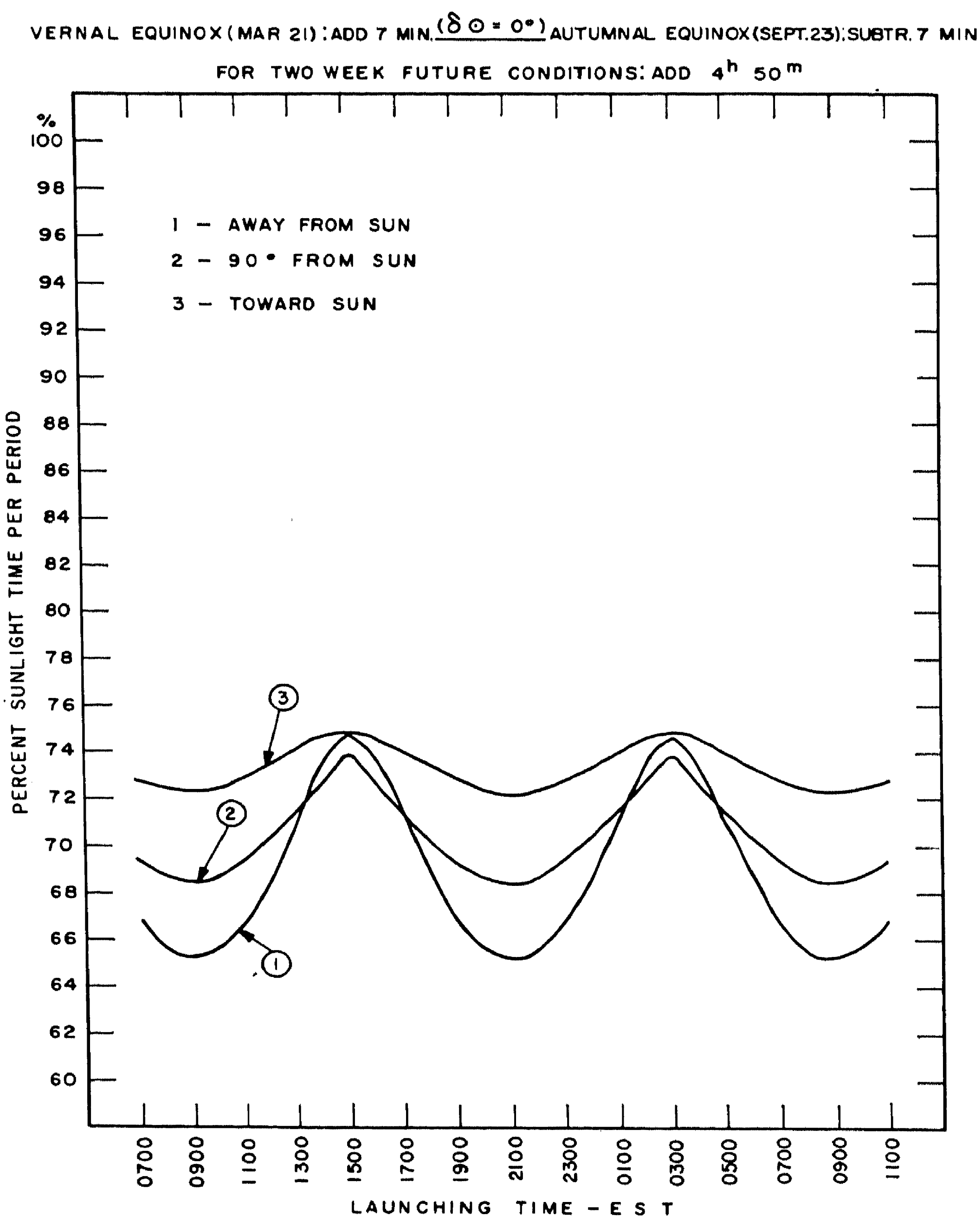

FIG. 5 — Per cent of time in sunlight for 200– to 1500–mi orbit for launching at equinox

input to the satellite, thereby determining its temperature. There are two factors to be considered here: (1) the electronic equipment is sensitive to temperature and will operate satisfactorily only between reasonable temperature limits, (2) some of the experiments must observe the Sun. As will be seen, the control that is left to us once the inclination of the orbit has been chosen is that of launching time and date. In order to have available a sufficient picture for judging suitable launching times of day for all times of the year, a great number of particular solutions to this problem have been computed. These have been combined on many different charts for convenient use.

The computations necessary to produce useful guiding charts have been made for three orbits considered typical for this problem: (a) a circular orbit at 200-mi height; (b) 200- to 800-mi elliptical orbit; (c) 200- to 1500-mile elliptical orbit. For each case conditions at all launching times of day have been computed at twelve different dates of the year, when the solar declination is 0°, ±10°, ±20° and ±23.5°. Typical curves resulting from these studies are shown in the next three figures (Fig. 5–7). The first

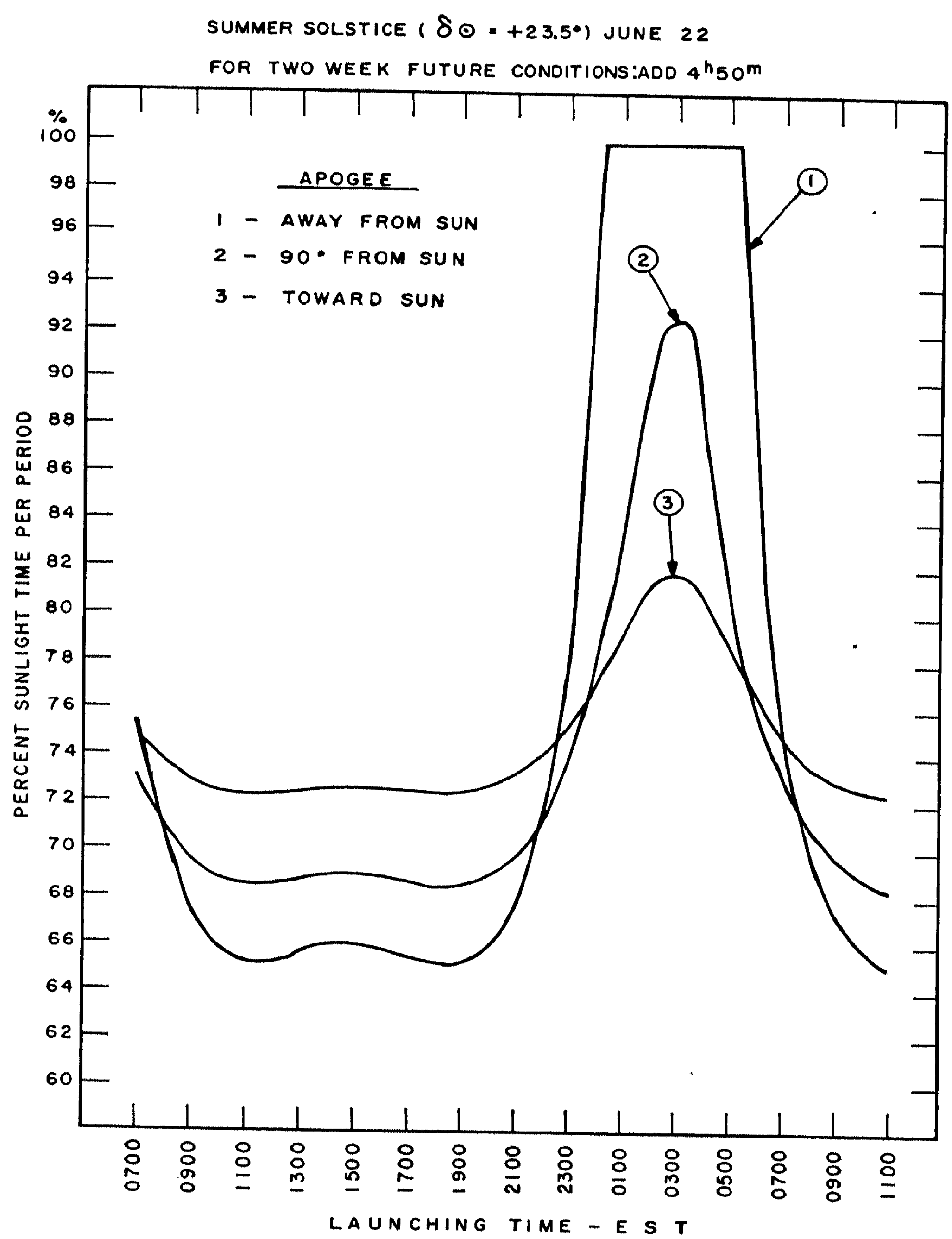

FIG. 6 — Per cent of time in sunlight for 200– to 1500–mi orbit for launching at summer solstice

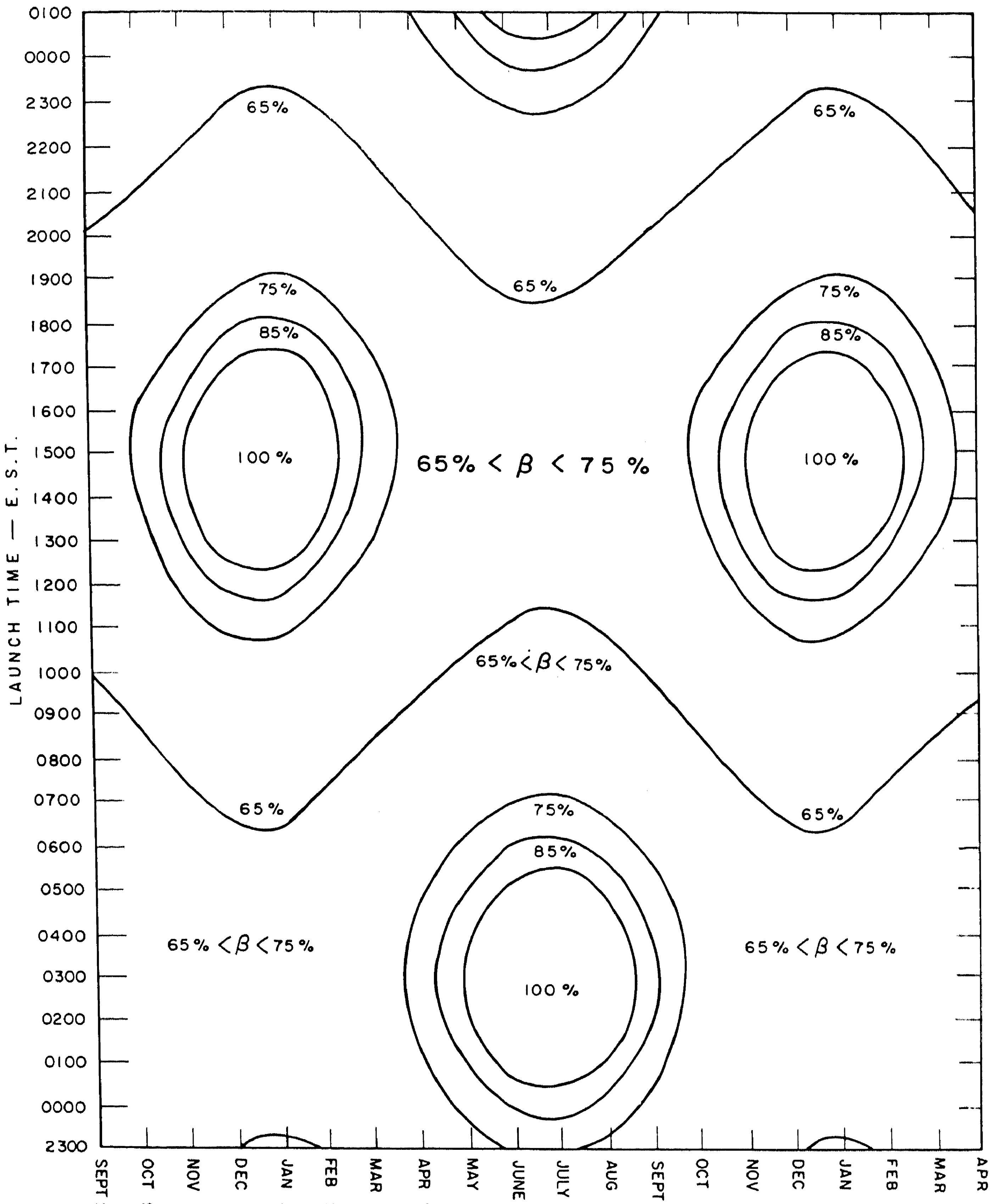

FIG. 7 — Summary of per cent of time in sunlight for 200– to 1500–mi orbit, apogee away from Sun

of these is drawn for the time of the equinox, the three curves referring to the position of apogee. Figure 6 is drawn for the time of the summer solstice when the solar declination has its greatest possible value, 23.5°. It is seen here that during one period covering more than two hours, it would be possible to put a satellite in an orbit continuously in sunlight. Figure 7 shows a summary of this information with the launching date as the abcissa and launching time as the ordinate. From this Figure it is clear that if it is desired to keep the satellite out of sunlight for a period of time, it is necessary to take care in the actual time of launching. There are three factors which must be considered in choosing the probable time of launching of each of the vehicles: (1) visual acquisition of the satellite by chosen moonwatch stations at the time of morning or evening twilight, (2) the necessity to avoid initially excessive time in sunlight during each orbital revolution so as to prevent failure of electronic components in the satellite owing to overheating, and (3) the requirement for several of the satellite experiments that the orientation of the spinning satellite relative to the sun will be compatible with the experiment. It will be attempted to meet all of these conditions but it must be recognized that unforeseen and unpredictable delays frequently occur in rocket launchings. This is to be anticipated especially in this vehicle which is rather complex with its three active stages.

Satellite temperatures—The satellite when in orbit is isolated and can gain and lose power significantly only by means of radiation. Aerodynamic heating will be negligible. The major sources of radiant power are the Sun, sunlight reflected from the Earth, and the Earth's radiation itself. Radiation from each of these sources is incident on the orbiting satellite and is absorbed by the shell. Power is lost from the satellite system only as infrared thermal radiation from the shell. The temperature of the shell is, therefore, determined by radiation balance. If the internal package temperature is different from that of the shell, then the package will either accept or contribute to the power and modify the shell temperature slightly, but the significant factor for the shell is the external radiation field. Since the only method by which the shell can lose energy is by radiation in the infrared, then it is clear that the way to control the temperature of the satellite is to control its infrared emissivity.

The internal package temperature is a function of the internal power dissipation, the thermal isolation between package and shell, and the shell temperature. The emissivity of the external surface of the satellite shell will be modified through the application of a thin coating of silicon monoxide which is transparent in the visible, but opaque in the infrared. With the proper choice of thickness for this coating the current conclusion is that the mean shell temperature will fall somewhere within a range of 50°C for all possible orbit parameters. The current choice for the range of temperatures for the satellite is $-15°$ to $+35°$C. With the shell going through this excursion in temperature, the internal package will remain within the limits of $-5°$ to $+45°$C. This will be satisfactory for the electronics, the batteries, and for the scientific experiment, at least for the first satellite. Therefore, no further system of control is proposed for the satellite. If it becomes necessary, a heat switch now under development could be inserted between the package and the shell and thereby further control the package temperature.

Magnetic damping of satellite rotational velocity—The third stage of the rocket will be spun about its longitudinal axis in order to stabilize its flight, and some of this spin will be imparted to the satellite. After separation the satellite will be a spinning conducting body in the Earth's magnetic field and there will be a loss of energy in the form of heat produced by induced eddy currents. The reaction of this induced force will take energy from the satellite's rotational motion and thus slow the angular velocity of rotation. Some theoretical work has been done on this problem and calculations show that the satellite will reduce its spin velocity to $1/e$ of the initial value in about one week.

Satellites—There are four different satellite designs being made for the six launching attempts. The current group-one satellite will be described as typical of the four. Figure 8 shows a cutaway drawing of this satellite as it is being constructed. The highly polished silicon-monoxide coated 20-inch magnesium sphere weighs about 21½ lb and has four antennas mounted 90° apart at the equator. These antennas are fastened by tubular rods to a tubular ring which is concentric with a cylindrical internal package. This inner package holds the electronic circuits

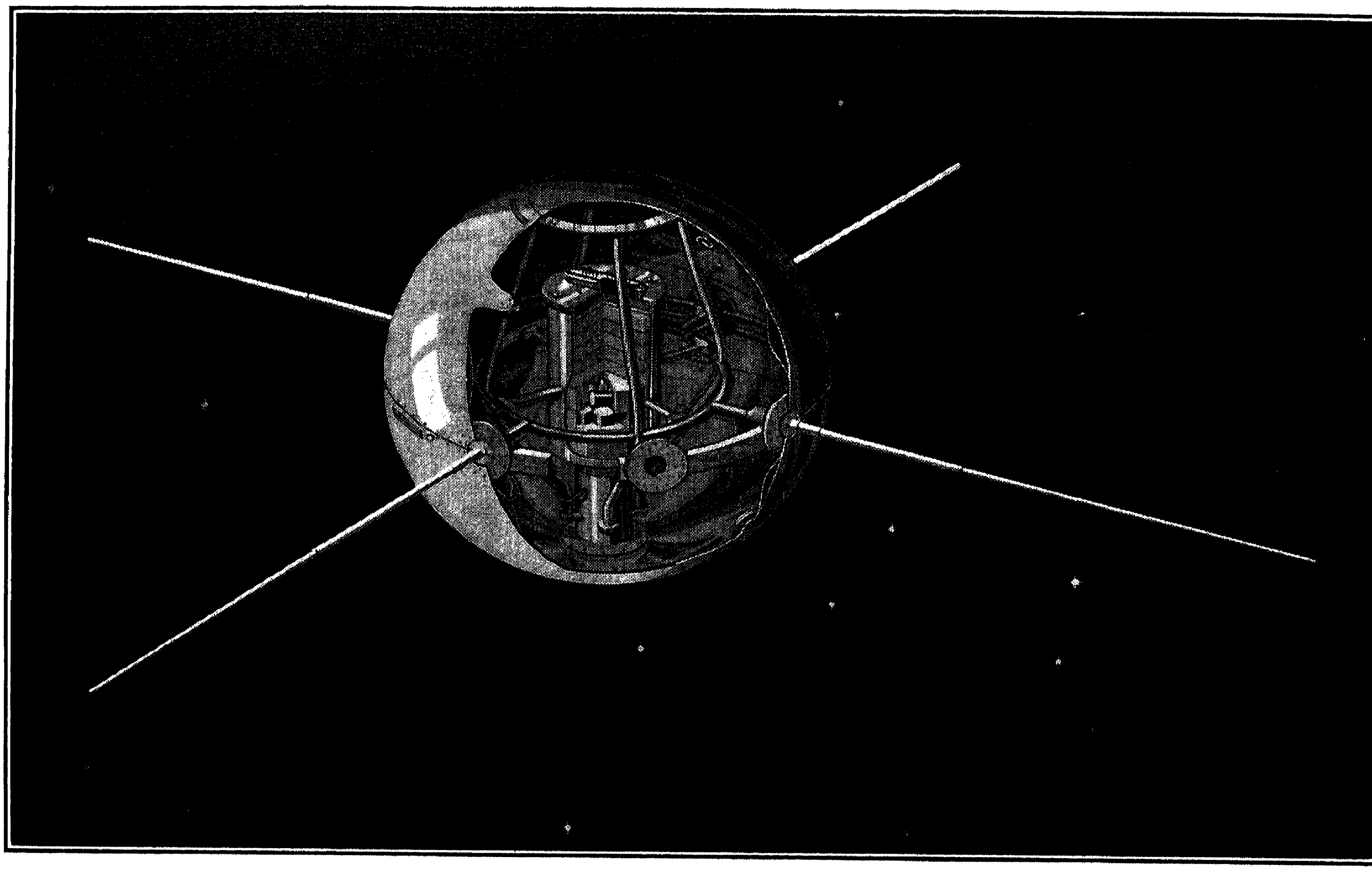

FIG. 8 — Typical Vanguard satellite

for the Minitrack transmitter and the scientific experiments, and the batteries. The ring supporting the central package is also supported by four bow-shaped vertical tubular members spaced 90° apart at angles of 45° to the antenna supports. These vertical members are fastened to the support ring of the access port at the top and to the main support column which houses the separation mechanism at the bottom.

The sphere is girded by two pressure zones or bands, one below the equator and one above. On the shell are the sensing elements for the ultraviolet experiments and the environmental experiments which are to be done in this group-one satellite. Included in the internal package are modules each 0.6 inch thick. One module is for the Minitrack transmitter and its associated electronics, one module for the Lyman-alpha electronics and batteries, one for the coded 48-channel telemetering system, one for the peak memory and orbital switch, and one for the meteor counter. Below these five modules are the battery packages. One battery package is $1\frac{5}{16}$ nches thick, the other $2\frac{1}{2}$ inches thick. These seven modules are held to the top cover of the internal package through two rods $\frac{1}{4}$ inch in diameter. On the top cover of the internal package are the connectors which serve to connect the gages on the skin to the electronics and also connect the batteries with the electronics, thus acting as a turn-on switch. While the entire satellite weighs $21\frac{1}{2}$ lbs the cylinder carrying the internal electronics weighs approximately ten pounds.

The four antennas which extend from the sphere are connected to the Minitrack transmitter. These antennas must be capable of being stowed out of position during the launching of the vehicle. To accomplish this the antennas are on a spring support, are folded forward in the nose cone, and as the nose cone is jettisoned the antennas snap down into their equatorial position and fit snugly on conical supports.

It is intended to separate the satellite from the third stage by means of a mechanism shown in Figure 9. This completely self-contained mechanism fits into the socket at the satellite's base, and uses the acceleration characteristics of the third stage as a method of arming and operation. After this acceleration is reduced below a fixed level, the timer in the separation mechanism starts to run and, after approximately 26 sec,

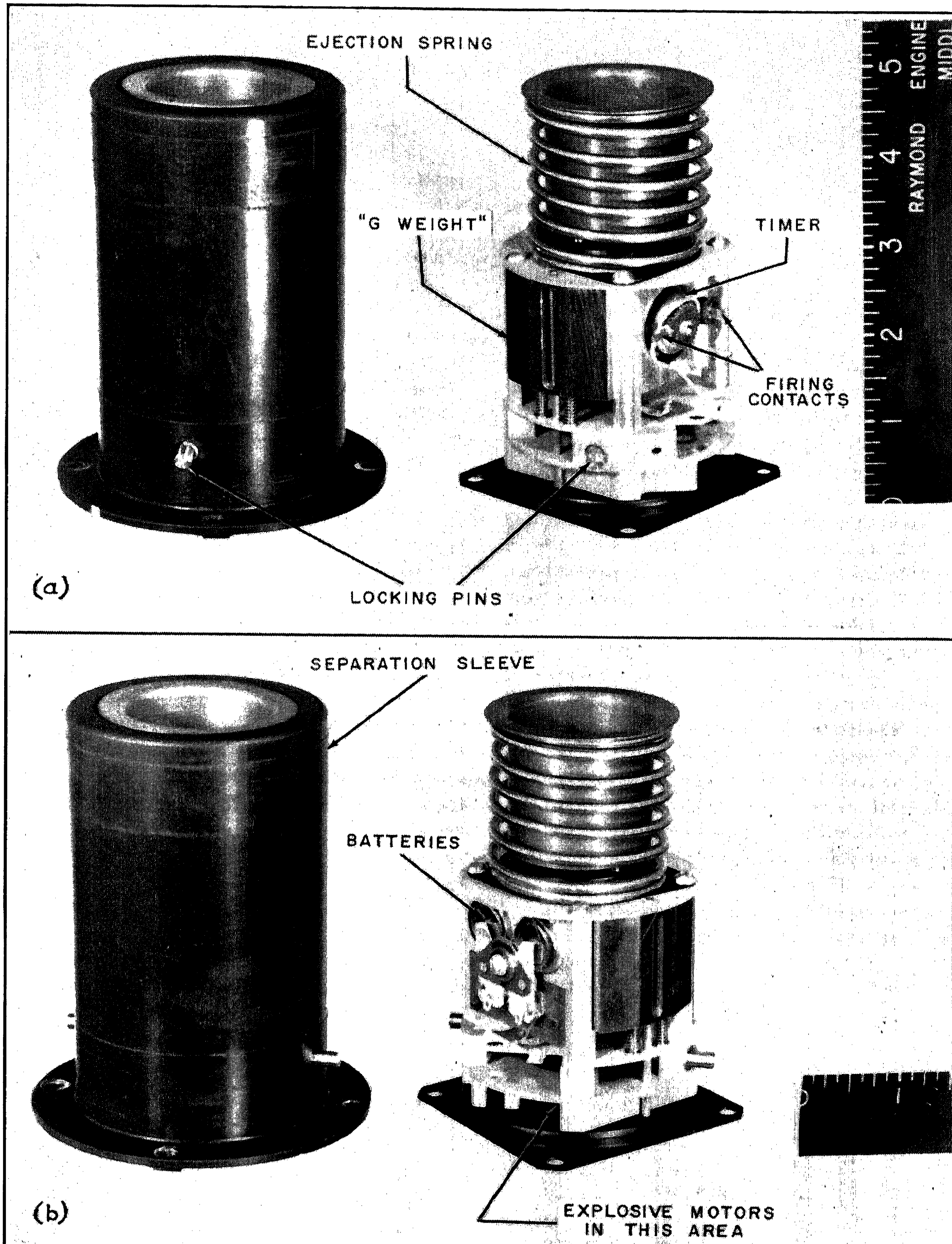

Fig. 9 — Satellite separation mechanism (a) front view; (b) rear view

closes circuits to motors within the mechanism which pull the hold-down pins and rotate the spring release. The spring exerts a force which imparts a relative velocity of approximately three feet per second between the satellite and the empty rocket case.

Satellite launching vehicle—The requirement that the Earth satellite be established during the International Geophysical Year imposed grave limitations on the developmental approach to the design of the launching vehicle. It was obviously desirable to use as many off-the-shelf components as possible, to use a configuration for which much of the preliminary design had already been done, and to employ a rocket vehicle contractor who had intimate and recent experience in the design and manufacture of research rocket vehicles and who had experienced engineering personnel. A study which had been made of a modification of the Viking design showed it applicable for use as a high-altitude research rocket. The first task which had to be accomplished was the translation of payload and orbital requirements into a vehicle and a plan for its employment to achieve the mission. It was then necessary to determine those elements which involved developmental effort, to arrange for their procurement and their integration into a vehicle, and to evaluate their performance.

A three-stage configuration was selected for the Vanguard launching vehicle. A theoretical analysis of staging (Fig. 10) shows that for the same gross weight, performance, and payload, the velocity gain over a single stage is 33 pct for two stages, 45 pct for three stages, and only 70 pct for an infinite number of stages. This improvement with a number of stages is due to the fact that the early stages are discarded as soon as their propellants are consumed, thus making it necessary for the later stages to accelerate less and less mass. Because of the added complexity of additional stages, it was decided to limit the combination being considered to vehicles having three stages or less. A single-stage rocket that flies all the way into the orbit would be the simplest configuration, but such a rocket is not realizable with propulsion that could be obtained from chemical combustion.

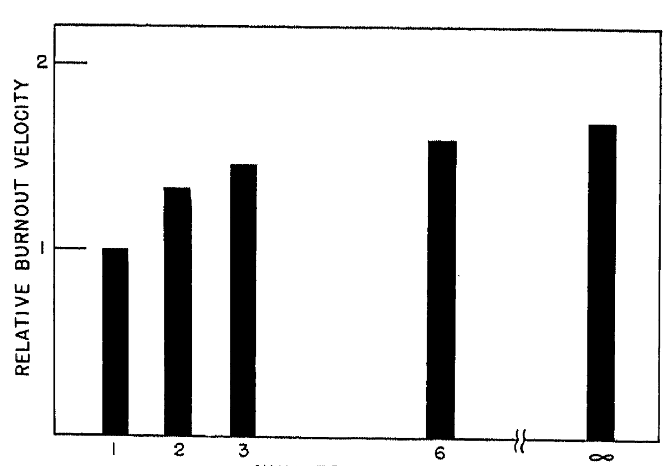

FIG. 10 — Analysis of staging and vehicle performance

The other basic decision which had to be made was the extent to which active guidance would be employed, or more simply, the number of stages that would be guided. This decision influenced the character of each stage, its size and complexity, and whether it should employ liquid or solid propellants. The various categories, depending upon the method of guidance, into which two-stage and three-stage rocket combinations may fall were analyzed on the basis of vehicle size and complexity. A three-stage combination employing liquid propellants in the first and second stages and a solid propellant in the third stage, with guidance in the second stage, was selected for the Vanguard configuration.

The vehicle which was defined had a minimum gross weight of approximately 20,000 lb. The minimum thrust for the first stage, to assure a safe initial (takeoff) acceleration was chosen as 27,000 lb. An engine with this thrust was promptly selected for use in the first stage, and its choice dictated to a large degree the characteristics of the remaining propulsion systems.

Stage weight and performance criteria, once the first-stage gross weight and thrust were fixed, were determined by the employment of weight and trajectory optimization techniques. The values established as initial targets in the Vanguard vehicle specification are reproduced in Table 1; some of them have since been re-

TABLE 1

Vanguard weight and performance data, gross weight 22,600 lb

Weight and performance elements	First stage	Second stage	Third stage
Thrust, lb	27,000	7,500	2,350
Burning time, sec.....	146	120	30
Horizontal velocity increment, ft/sec	4,023	8,389	13,405

vised slightly as a result of the development program.

To assure a reasonable acceleration at the separation of the second stage from the first, a nominal second-stage thrust of 7500 lb was selected. The state of the art dictated a liquid-propellant rocket. The problems associated with ignition of the powerplant made a hypergolic fuel combination and simplicity of design mandatory. A package concept was established to allow testing of the system as a whole on the ground and to facilitate the establishment of vibrational characteristics needed for control-system design. A gas-pressurized system which employed nitric acid and unsymmetrical dimethyl-hydrazine as propellants was sought. It had been hoped originally that an Aerobee-Hi powerplant nearing completion at that time would meet the requirements for this stage. However, this powerplant could not be modified to meet the strenuous requirements specified. The Aerojet General Corporation was selected to develop and manufacture a second-stage powerplant to meet the desired specification.

The severe weight penalty associated with the third stage (80 ft/sec lb) which led to the decision to house the rocket-borne guidance components in the second stage and the decision to spin the third stage to maintain its orientation during burning, made the use of a solid-propellant rocket highly desirable for this stage. High mass ratio, approximate axial symmetry throughout burning, and the absence of 'sloshing' effects rendered internal burning solid rockets particularly adapted to this type of employment. Several solid-propellant producers submitted proposals for this stage. Because of the anticipated difficulty of this development, two contractors, the Allegany Ballistics Laboratory of the Hercules Powder Co., Cumberland, Md. and the Grand Central Rocket Co. of Redlands, Calif., were selected to conduct parallel efforts.

The flight plan initially prescribed for the launching vehicle was: (a) Vertical flight from launching until satisfactory clearance of ground installations has been attained. (b) After reaching this point, an approximate zero-normal-force trajectory until aerodynamic forces are no longer critical. (c) The first stage is to be separated from the second stage as soon after burnout as practicable within the limits of first-stage shutdown and second-stage startup characteristics. (d) In the later part of second-stage powered flight the nose cone is to be jettisoned. (e) Pitch-over during the second-stage post-cutoff flight is to align the vehicle so that the third-stage velocity vector at the time of third-stage burnout will be parallel to the local horizontal within the limitations imposed by Figure 4. (f) After second-stage separation, the third stage is to increase its velocity sufficiently to insure attainment of the prescribed satellite orbit. (g) When orbital velocity is attained, the third stage is to be separated from the satellite. The trajectory associated with this flight plan is shown in Figure 11.

The prescribed flight plan and the method of employment of the various powerplants established the detailed guidance and control requirements. In addition to attitude controls for the first-stage powered flight and for second-stage powered and coasting flight, it was found necessary to include (a) a programmer which would introduce, in accordance with a prescribed plan, a pitch-program rate change to secure the optimum trajectory and rocket-staging events, and (b) a coasting-time computer which would, on the basis of integrated acceleration, establish the optimum time for ignition of the third-stage rocket.

The use of the gimballed motor as a means of obtaining pitch and yaw correction moments is a technique amply proved during the Viking development. The finless configuration, while untried at the time, was selected. It had been studied carefully during the Viking development and appeared to be technically feasible and practicable. The autopilots involved are basically similar to those employed on Viking; the 'rocket dynamics' are obviously different and require appropriate compensation.

The system of guidance finally adopted is not totally dependent on rocket-borne instruments but provides an alternate means of adjusting the ignition time of the third stage from the ground.

The Martin Co., Baltimore, Md., was selected as prime contractor for the Vanguard launching vehicle. This assignment carried with it overall responsibility for development of the vehicle, including all subcontracting with the exception of electronic components associated with the acquisition of flight-performance data and with range safety and tracking functions. Not one propulsion system, but three were required. Guidance and controls could not be designed to one vehicle whose dynamics change

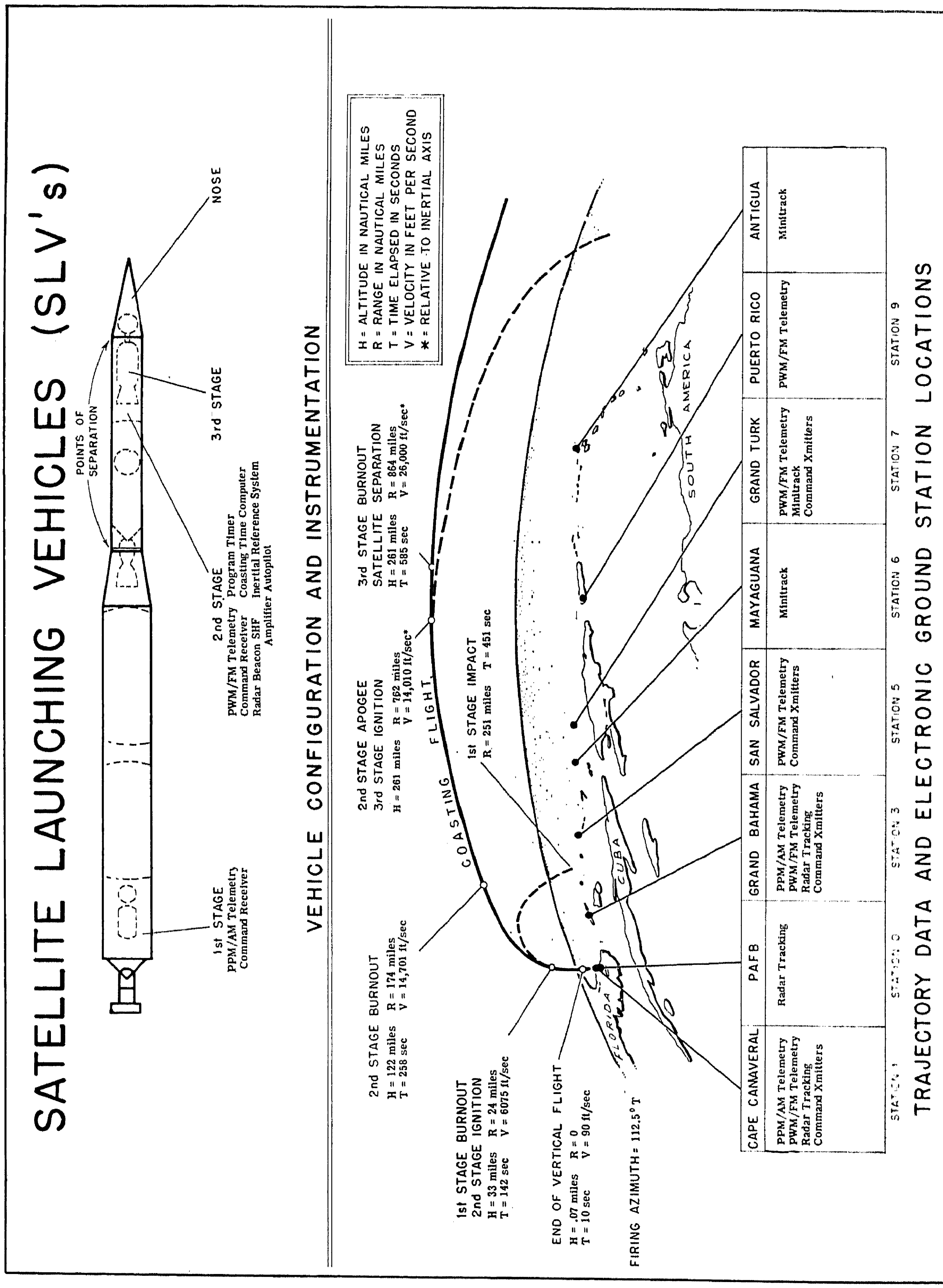

FIG. 11 — Schematic of satellite launching vehicle and details of launching trajectory

continuously through the flight regime, but must be tailored to three vehicles whose dynamics vary differently and go through sharp transitions. Structural problems were aggravated by these transitions and by the extreme demands for weight minimization particularly characteristic of this development. The integration of stages and the necessity for some components to perform dual roles have made their requirements more exacting than those ordinarily encountered.

The prime contractor, to meet the requirements for this vehicle, had to perform or arrange for the design, construction, qualification, and integration into an over-all system of the following basic components and systems: three propulsion systems, an overall guidance system, an inertial reference, a flight programmer, a coasting-time computer, and two separation systems.

The prime contractor has included in his developmental program as comprehensive a program of design confirmation, environmental qualification, and acceptance tests and studies as time will allow, to reduce to a minimum the number of test objectives which will require flight testing. Included have been aerodynamic studies and windtunnel tests, structural analyses and tests, vibration analyses and tests, dynamic mockup tests and functional tests of all major systems. Weight optimization and trajectory optimization studies have been pursued by both the contractor and the Laboratory.

The composite Vanguard launching vehicle has an over-all length of approximately 72 ft; a first-stage maximum diameter of 45 inches and a second-stage diameter of 32 inches. Its slenderness ratio is therefore about 19 to 1, approximately equal to the initial Viking configuration. It is finless, of integral tank construction, and has a gross takeoff weight (with propellants) of 22,600 lb.

The first stage is a liquid-propellant rocket similar to the Viking, but with substantial changes. Its major propellants, liquid oxygen and kerosene, are fed to the rocket motor by turbine driven pumps. The motor is gimballed, as in the Viking, to provide continuous control of the vehicle's orientation and flight path. The electrohydraulic controls that position the motor have the necessary response to stabilize the composite finless airframe in pitch and yaw. Roll control is provided by a periodic controller which divides and changes the direction of the turbine exhaust thrust so as to produce a correcting couple about the vehicle's longitudinal axis whenever roll errors and error rates exceed a specified sum. Guidance information is obtained from an inertial reference system, carried in the second stage. In essence, the first stage is a guided liquid-propellant booster which provides about 65 pct of the energy to raise the remaining stages to orbital altitude and about 15 pct of the required orbital velocity.

The second stage is a liquid-propellant rocket that attaches to the forward end of the first stage and carries in its nose the third stage and satellite payload. Its propellants, white fuming nitric acid and unsymmetrical dimethyl-hydrazine, are fed directly to the motor from high-pressure integral tanks. The pressurizing gas is helium, as in the first stage. The motor is gimballed, as in the first stage, and it is positioned in pitch and yaw by electrohydraulic controls. An array of gas jets provides roll control during second-stage powered flight and complete control of vehicle orientation during coasting flight. The reference system is located wholly within the second stage. The flight programmer initiates at the proper time all major in-flight operations, switching the program (pitch) rates at the prescribed flight times. The guidance and control equipment, housed in the second stage, align and maintain the second stage during its coasting flight to the proper orientation for the launching of the third stage.

The second stage houses within its nose, which is the nose of the composite vehicle, the third-stage rocket and the satellite. The nose cone protects the delicate satellite sphere from aerodynamic heating it would encounter, if exposed, during the first- and second-stage ascent through the atmosphere. The cone is jettisoned after 180 sec of flight, after which exposure of the satellite will not be detrimental. The mechanism for spinning the third stage is carried also in the second stage.

The second stage thus contains the 'brain' of the launching vehicle. It also supplies the remaining energy required to reach orbital altitude and about 32 pct of the orbital velocity.

The third stage is an unguided solid-propellant rocket that is maintained during burning in a stable orientation very nearly parallel to the Earth's surface, by spinning it about its longitudinal axis. The third stage is fired at orbital altitude and provides 50 pct of the required

orbital velocity. Approximately three per cent of the orbital velocity arises from such geophysical effects as the Earth's rotation.

Launching program—Prior to the six satellite launching attempts there is a flight-test program which involves the launching of seven test vehicles. With these vehicles all of the components and component assemblies, the telemetry and tracking, which are to be used later in the satellite launching vehicles are given a flight test. The design of the test vehicles becomes gradually more complex until toward the end this design phases into the satellite launching vehicle design. The rigorous schedule imposed by the requirement to launch a satellite during the period of the International Geophysical Year has made necessary a streamlined test program.

The test vehicle and satellite launching vehicles will be launched from the Air Force test launching station in Florida with the assistance of the Air Force. A hangar for vehicle assembly and a launching complex for firing the vehicles have been constructed and assigned to this operation. Major components are a pad for the launching of the vehicle with provisions for the necessary controls at the time of launching and for the deflection of the hot gases in the initial stages of the flight, a gantry crane which surrounds the vehicle up until the time of launching when it is withdrawn, and a blockhouse for the accommodation and protection of the personnel at the time of launching.

The trajectory of the launching vehicles will carry the vehicle to the southeast of Florida along the string of islands in the West Indies. On many of these islands apparatus has been installed to receive telemetered signals from the launching vehicle and to transmit commands to the vehicle during its course. The last of the stations is on Antigua. This is a Minitrack station and is so located that here will be the first measurement of the velocity of the satellite at the end of third-stage burning. While the accuracy of the measurement on this short baseline possibly is not high enough to assure that orbiting velocity and direction have been attained, nevertheless, the measurement will be good enough to give us a first indication and to determine whether the other optical and radio tracking stations should be alerted.

The work of many of the members of the Vanguard group has been drawn heavily upon in preparing this paper and I would like here to acknowledge the contributions to all of them with a special emphasis on the contributions of Joseph Siry and Milton Rosen.

Addendum, May 20, 1958—Since this paper was presented, six artificial Earth satellites have been placed in orbit: three by the Soviet Union and three by the United States. One of the latter was a small test sphere whose launching inaugurated the final phase of the Vanguard vehicle test program. Because of the light weight ($3\frac{1}{4}$ lb) of this sphere and the excellent performance of the Vanguard launching vehicle TV-4, the orbit is very high; both the perigee, 404 mi, and the apogee, 2464 mi, are the highest produced to date. The early 1400-mi limitation on the apogee for Vanguard was removed when the development of the radio tracking system assured adequate tracking capability at much greater ranges.

Measurements of the rate of change in this satellite's period of revolution indicate that its orbital lifetime will be at least 200 years. With its spherical shape and with so stable an orbit, this satellite should prove a useful one for geodetic and air-density studies. It carries two Minitrack transmitters, one battery-powered (exhausted after three weeks of continuous operation) and the other solar-powered; the latter will radiate on a frequency of 108 megacycles for as long as it escapes damage by environmental conditions. Both transmitters utilize temperature-sensitive crystals, and careful measurements of their frequencies have provided the internal and the shell temperature of the satellite; temperature measurement continues with the solar-powered transmitter.

As was to be expected, not all of the vehicles launched in the Vanguard test program were entirely successful; two unsuccessful attempts preceded the successful TV-4, and in the final test launching, TV-5, an electrical malfunction prevented the firing of the third-stage rocket after the first two stages had performed excellently. However, with appropriate measures taken to correct the difficulties encountered in the test flights, the test program is now concluded and the scientific satellite launching program is about to begin. Before this is printed, the first attempt will have been made to launch a full-scale Vanguard IGY satellite.

U. S. Naval Research Laboratory, Washington, D. C.

The United States Satellite Tracking Program

W. H. Pickering

Introduction—An important part of the satellite scientific program is the analysis of the satellite orbit. Precise observations of this orbit can yield results of extraordinary geophysical interest. The unique feature of the satellite orbit is that, in astronomical terms, it is so close to the Earth that it is located in a gravitational field which is not simply the field of a central mass point, but the actual field caused by a nonspherical, nonuniform Earth. Its motion is therefore not a simple Keplerian ellipse fixed in inertial space. Analysis of this motion will provide geodesists with new data on the gravitational potential in the vicinity of the Earth and, therefore, of the precise shape of the Earth.

The orbital motion will also be affected by the drag of the atmosphere remaining at the satellite height. This drag will cause a loss of energy and the satellite will eventually re-enter the dense atmosphere and be destroyed. Our knowledge of the atmosphere at satellite altitudes is quite indirect and therefore again the new data from the satellite trajectory will be of great value.

In order to obtain useful data, the observations must be of an accuracy comparable with good astronomical observations. For example, a position accuracy of the order of ten feet at the trajectory would correspond to an angular accuracy of the observations of the order of one second of arc. Such an accuracy is not too difficult for optical instruments except that the satellite is moving at 25,000 ft/sec and therefore a timing accuracy of better than one-half millisecond is required to correspond to a motion of ten feet along the trajectory. Orbital data of this accuracy would result in geodetic information of a quality not now available except in a few limited regions of the Earth's surface.

Satellite Acquisition

When the satellite is launched, the instrumentation at the launching site, Cape Canaveral, Florida, will provide an approximate estimate of the orbit. Presumably the tracking of the second stage will be quite accurate; however, the crucial information for the orbit is dependent upon a knowledge of the vector velocity increment of the third stage. To obtain these data, the third stage must be tracked, either visually or by means of satellite transmitters. Visual observations will only be possible if the firing is at night, so that the rocket flame can be photographed. Radio observations require that the satellite radio beacon operate correctly during the high-acceleration, high-vibration phase of the flight. It is therefore difficult to estimate with what assurance the orbit will be known immediately after the firing. Accordingly it is planned to use a widespread network of both optical and radio observers to assist in the problem of acquiring the satellite and finding its approximate path. Both groups will be primarily amateurs, organized into teams capable of making useful observations of high reliability.

Visual observers—To date, the primary emphasis has been on the organizing of amateur astronomers into satellite observing teams. The activity is known as Project Moonwatch, directed by the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. About 80 teams are scattered across the United States. Teams are also being formed in some 22 other nations throughout the world which are favorably located for visual observations. Each team consists of 15 or more observers equipped with binoculars or small telescopes (Fig. 1). The instruments are mounted firmly on fixed supports so that each observer is looking at a fixed region on the sky in the meridian plane. The complete set of instruments is then arranged to give overlapping coverage along the meridian plane. In this way the passage of the satellite through the meridian of the station will be observed by at least one observer. The observer marks the instant of meridian passage and, also by noting the star background, the approximate zenith angle of the satellite. These data, which it is hoped will be accurate to at least one second of time and one degree of arc, will be telephoned immediately to the Smithsonian Observatory where they will be analyzed and used to establish the approximate orbit.

FIG. 1 — Photograph of MOONWATCH station

Information on Project MOONWATCH has been widely disseminated through the journal *Sky and Telescope,* and a special *Bulletin for Visual Observers of Satellites* issued by the Smithsonian Observatory. A nationwide practice alert was held in May with encouraging results.

The MOONWATCH organization will be needed not only at the beginning of the satellite's life, but also at the end. By this time any radio equipment aboard the satellite will have exhausted its batteries, and the only means of observation will be optical. There will be considerable interest in the exact nature of the final path taken by the object as it plunges into the dense atmosphere. Even though the orbit has been well established, this path will be only roughly predictable. It is therefore hoped that MOONWATCH stations all over the Earth can be alerted to follow the final crucial days of the satellite. Only in this way can vital information be obtained on the air density at altitudes significantly below the original perigee altitude.

Radio observers—The satellite is expected to carry a radio transmitter and this signal will be tracked by the prime radio network, the Minitrack stations along the 75th meridian. However, observations from other radio receiving stations could prove exceedingly valuable. The Naval Research Laboratory will shortly publish information on what is known as the Mark II Minitrack, a simpler system than the prime Minitrack stations. Mark II Minitrack stations will be set up at a number of locations around the world. To date inquiries concerning Mark II stations have been received from a number of nations including France, South Africa, Japan, Australia, and England, as well as numerous groups within the United States.

Amateur radio stations within the United States are also being organized to contribute to the satellite program. A radio station more appropriate to amateur use is a modification of the Jet Propulsion Laboratory's Microlock system [*Richter, Sampson* and *Stevens,* 1957]. Such a station has been built by the San Gabriel Valley Radio Club and is ready for operation

(Fig. 2). A description of this station will be published in the amateur radio magazine *QST*. It is planned to build an amateur radio network along similar lines to the MOONWATCH network.

With both optical and radio observers at widely separated sites, it is hoped that the problem of the initial acquisition of the satellite will not prove too difficult. From these observations, the initial ephemeris will be calculated, and the precision observing stations will be alerted at the appropriate times.

PRECISION OBSERVATIONS

Precision measurements of the orbit will be made both optically and by radio. The optical method has the advantage of higher intrinsic accuracy but has a limited observing time. The radio method requires the satellite transmitter to be operating and, although the accuracy is lower, the object may be observed on every passage, regardless of time of day or weather conditions. It is therefore apparent that both techniques should be exploited fully.

Satellite camera—The basic optical instrument is a Schmidt-type camera with a special film-transport mechanism designed for the express purpose of satellite tracking. The camera was designed under the direction of Fred L. Whipple, Director of the Smithsonian Astrophysical Observatory. It utilizes a 20-inch apochromatic three-element corrector plate and a 31-inch spherical mirror.

The focal ratio of the camera will be f/1; the scale will be approximately 406 seconds of arc/mm. This instrument is expected to photograph rapidly moving satellites as faint as the 13th magnitude. A measuring accuracy of two seconds of arc is expected. An automatic film transport system permits the taking of successive exposures at 2- to 32-second intervals and permits exposures in relatively bright twilight sky.

A significant measurement to two seconds of arc requires a timing accuracy of 0.001 second of time. To achieve this accuracy each station will be equipped with a modified Norrman crystal clock which may be read by means of an oscilloscope to 0.0001 of a second. A time-display unit from this clock will be located within the body of the telescope and will be photographed on each film strip. More detailed information on the construction and operation of these instruments and the timing system will be found in the article entitled The Baker-Nunn Satellite Tracking Camera, [*Sky and Telescope*, Jan. 1957]. Figure 3 presents a sketch of the camera mechanism.

It will be possible to photograph the satellite only during the twilight periods when the satellite can be seen against a dark sky and will still

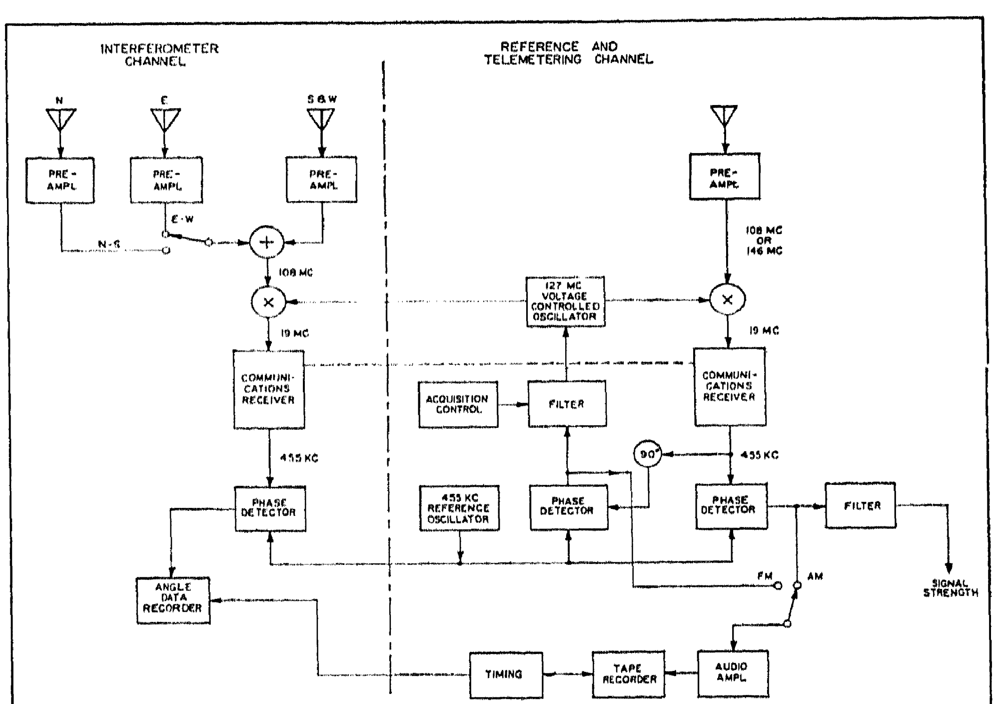

FIG. 2 — Block diagram of San Gabriel Valley Radio Club Microlock station

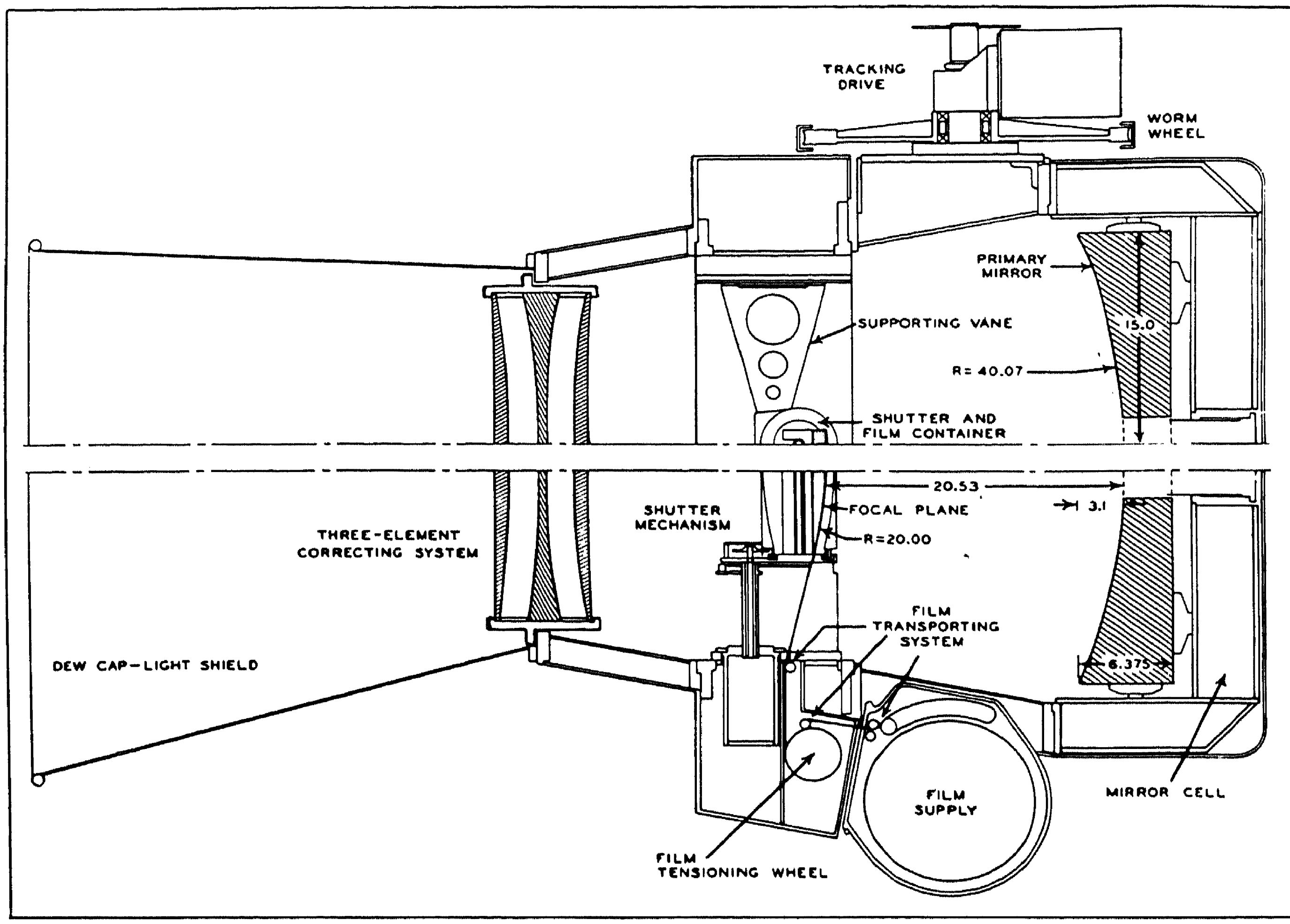

FIG. 3 — The precision camera mechanism (Courtesy of *Sky and Telescope*)

be high enough to reflect sunlight. For a station at a latitude of 30° and a satellite height of 800 mi, the satellite may be observed for at least two hours at morning and evening twilights. Thus, assuming a 100-minute period for the satellite, a station within observing range of the orbit during the twilight period is certain to make one observation of the satellite during the twilight interval and may possibly make two observations. A station at 30° latitude will see the orbit of the satellite at least 30° above its horizon during morning or evening twilight for approximately 28 days during each 70-day precession period. Taking into account the many factors involved including weather and season, it appears likely that an average station may expect to observe the satellite approximately 15 times in two months.

Calculations assuming a 20-inch specular satellite with a reflectivity of 0.6 indicate that, at the expected perigee height of 200 mi, the satellite will be about as bright as a 5.7 magnitude star. At any other altitude, the magnitude is given by $M = 5.7 + 5 \log d/200$. Thus at an altitude of 1000 miles the brightness is equivalent to a magnitude of 9.2. This brightness assumes an optimum geometry of the Sun, satellite, and the observer. The angular velocity of the satellite as seen from the Earth will, of course, depend upon the zenith angle and the altitude of the satellite. For an altitude of 200 mi and a point near the zenith, the angular velocity will be approximately $1\frac{1}{2}°$ per second.

In order to photograph this faint, rapidly moving object, a large field of view is required since it must be assumed that the predicted position of the object is no more accurate than about 1°. The Baker-Nunn camera has a field of $5° \times 30°$ which is photographed on a strip of 50-mm film about one foot long. With a focal length of 20 inches, an image diameter of 30 microns is required to fully utilize the camera's capability. In order to achieve this performance out to the edge of the field, a special Schmidt system was designed by J. G. Baker. The camera is mounted on a gimbal structure which

permits the long axis of the film to be oriented along the expected path of the satellite. It is planned to cause the camera to oscillate so that it will alternately track at the satellite rate and at the rate of sidereal motion parallel to the satellite orbit. In this way exposures on the satellite and on the background of faint stars can be made on a single film. The satellite can then be measured relative to nearby star images. Account can be taken of the satellite motion between the two exposures by measuring the distance between the 'star-exposure' images of the bright stars and the 'satellite-exposure' images of these same stars. This distance will never exceed one inch; the problem of film stretching is thus minimized.

It is important to provide sharp breaks in the trail as reference points for measurement and for time determination. These breaks will be produced by a rotating barrel shutter with all but two staves missing. This shutter is shown in the upper part of the camera diagram as the cylinder that encloses the film backup plate. Concentric with the barrel shutter and just outside it is a clamshell shutter which snaps open to begin and shuts to terminate each exposure.

The operation of the satellite tracking camera may be described in terms of a basic cycle in which the tracking rate varies from sidereal to satellite and back again. The length of this operating cycle may be set at 2, 4, 8, 16, or 32 sec. If the cycle begins just at the end of the star exposure, the following events occur in the order given:

The tracking rate accelerates until the satellite rate is reached. The clamshell shutter snaps open for an interval of 0.1 cycle, during which the exposure is chopped into four segments by the continuously rotating barrel shutter (which turns 20 times per cycle). At the instant of some one chop, a stroboscopic flash illuminates the time-display unit attached to the camera, and the time is photographed on the following strip of film through a small auxiliary optical system. After the clamshell closes, the tracking rate decelerates to the sidereal rate and the clamshell opens again for 0.1 cycle. This star exposure is likewise chopped into four segments but the time is not recorded. After the shutter closes again, the film is automatically changed and the cycle repeats.

At its greatest angular velocity, the satellite will move some 5300 seconds of arc per second of time. A measuring accuracy of two seconds of arc along the direction of motion would thus require time determination to 1/2500 second of time in this extreme case. It is impossible to achieve this precision in field operations but, clearly, the greatest possible accuracy must be strived for. The main component of the time unit installed with each telescope will be the Model III crystal clock manufactured by Ernst Norrman Laboratories, Williams Bay, Wisconsin.

The satellite-tracking cameras and the timing equipment are now under construction. The basic contractors are Perkin-Elmer Corporation, Norwalk, Connecticut, which is producing the optical components, and Boller and Chivens, Inc., South Pasadena, California, which is making the mechanical components. The crystal clocks and their accessories are being built by the Norrman Laboratories. The correcting-plate glass is being produced by the Schott optical glass works in West Germany, while the mirror blanks are coming from the Corning Glass Works, Corning, New York. The first optical system and its camera body and mount are expected by late summer.

It is planned to have twelve stations distributed about the world for photographic observation of the satellite. The locations of the observing sites are as follows: White Sands, New Mexico; Florida near Palm Beach; Curaçao, Netherlands West Indies; Arequipa, Peru; Villa Dolores, Argentina; Olifantsfontein, Union of South Africa; Cadiz, Spain; Shiraz-Teheran, Iran; Naini Tal, India; Woomera, Australia; Mitaka, Japan; Haleakala, Hawaii. Each station will be equipped with camera, clock, power supply, radio equipment, and the necessary supporting activities. Transportation of equipment to the stations is being provided by the Air Force. At the stations in other countries a great deal of technical assistance is being provided by local scientists.

The first camera will be installed at the site near White Sands, New Mexico, in the summer of 1957. By the end of 1957 cameras will be operating at seven sites. All stations should be in operation by March 1958.

Radio system—The Minitrack system is designed to track the very weak transmitted signal from the satellite, with high angular accuracy.

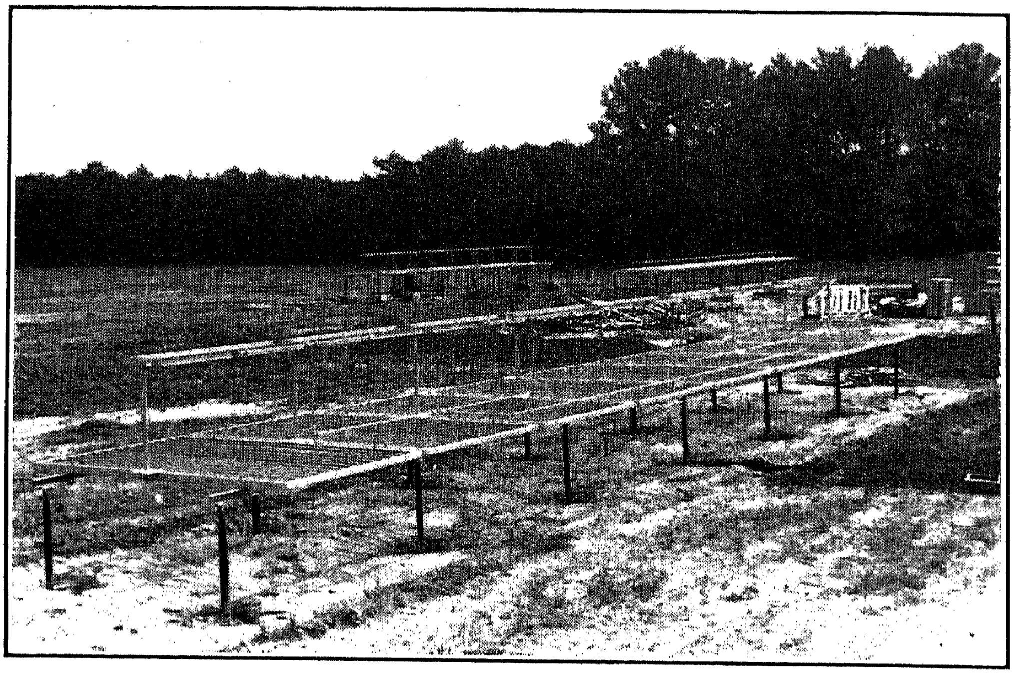

FIG. 4 — Antenna installation at Blossom Point, Md.

This system consists basically of a very sensitive receiving system and an array of antennas arranged to form an interferometer. Figure 4 is a photograph of the antenna installation at Blossom Point, Maryland, and Figure 5 is a sketch of the complete antenna field. Each antenna in the field is an array of eight driven elements forming a fan beam with about a 10° width in the east-west plane and a 100° width in the north-south plane. The basic interferometer is a cross with 500 ft separation between antennas. Four additional antennas are provided to resolve ambiguities, thus giving coarse, medium, and fine data in the north-south plane and medium and fine data in the east-west plane. Great care has to be taken with the feed lines in order to maintain the correct phase relationships over the whole field.

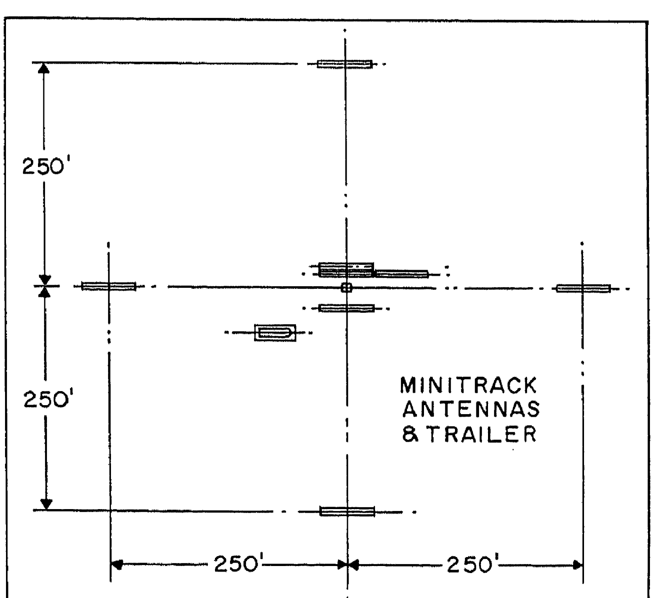

FIG. 5 — Sketch of complete Minitrack antenna field

In order to read the bearing angles of the transmitter a phase comparison is made between the outputs of the appropriate antennas. Figure 6 is a block diagram of the receiver. The essential feature of the receiver is a scheme to beat the signals down to 500 cycles and then measure phase against a reference 500 cycle tone. Output data will consist of digital readout of the 'fine' data and analogue data from the 'coarse' antenna pairs. Time will be measured to an accuracy of better than one millisecond. It is hoped to attain an angular accuracy of better than 0.1 milliradian. Calibration of each station will be required at intervals of a few months. This will probably be done with airplanes flying over the station at great altitudes, although the possibility of using radio stars is being explored.

The Minitrack program is under the direction of the Naval Research Laboratory. A station has been constructed at Blossom Point, Maryland, and has been in operation for almost a year. Equipment for other stations is being built by Bendix and the first units have been delivered (Fig. 7). This Minitrack network

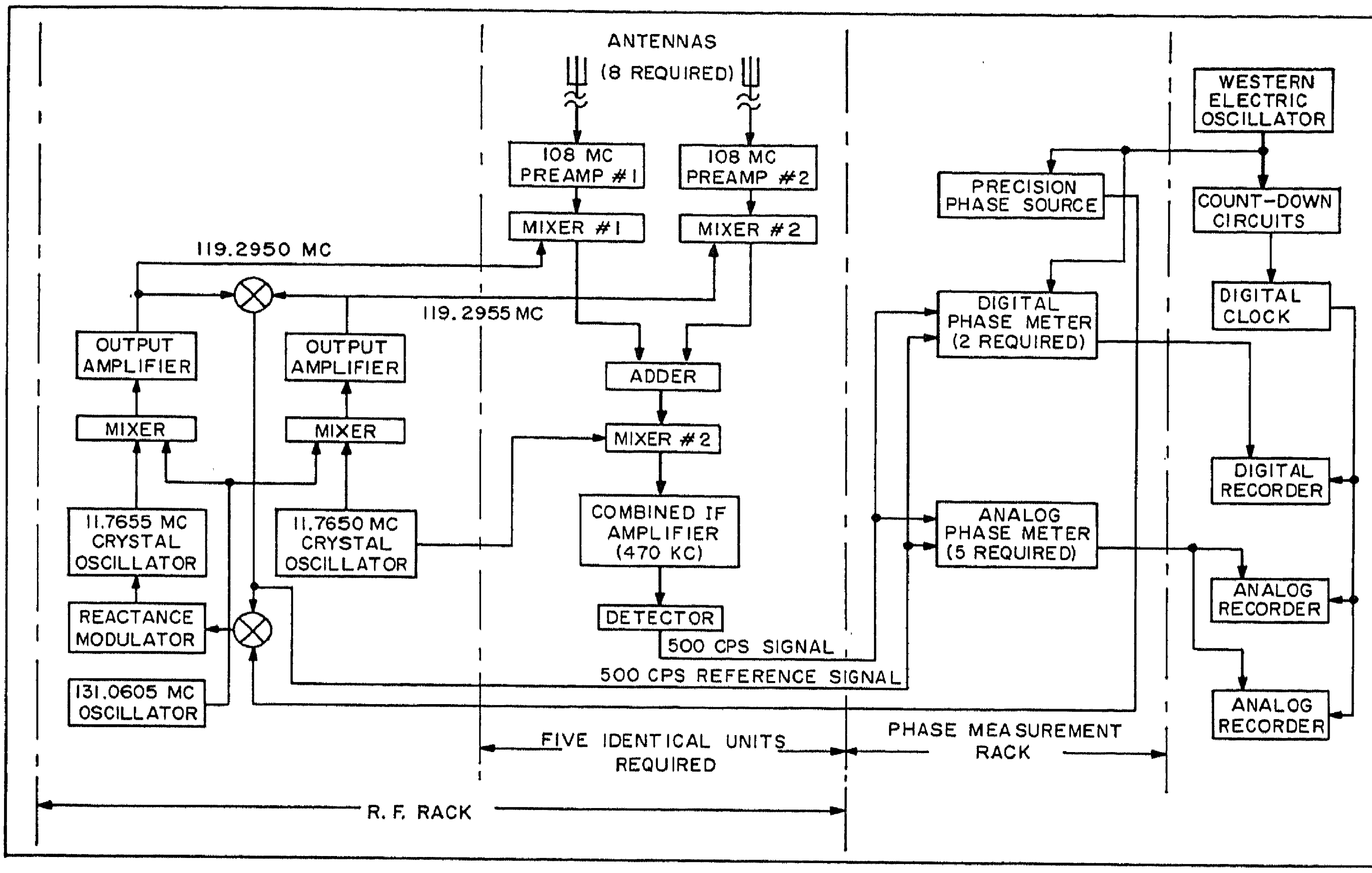

FIG. 6 — Block diagram of Minitrack receiver

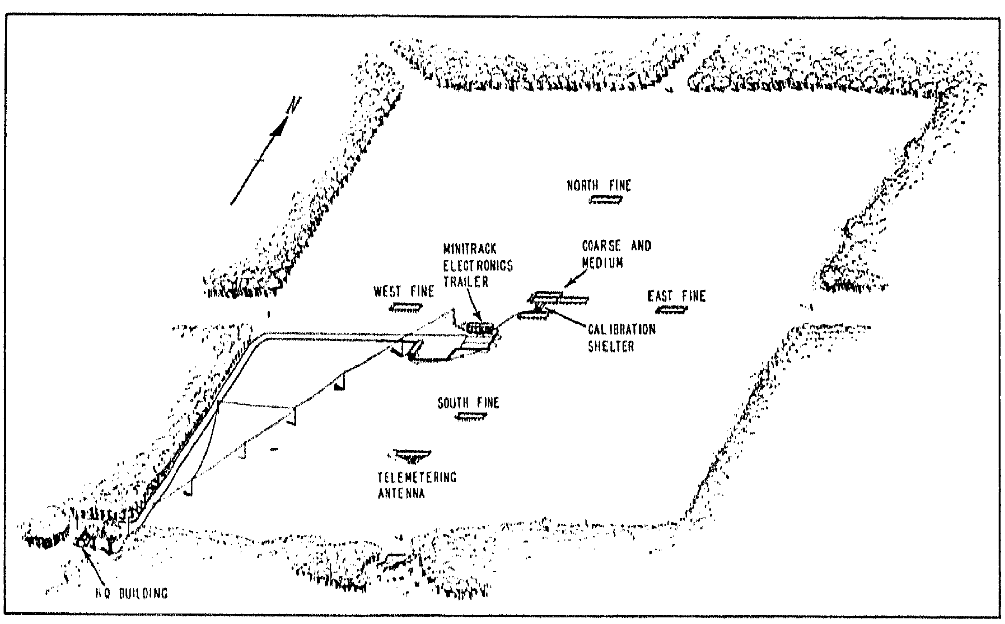

FIG. 7 — Typical Minitrack facility layout

consists of stations at the following locations: Blossom Point, Maryland; Fort Stewart, Georgia; Havana, Cuba; Antigua, the West Indies; Quito, Ecuador; Lima, Peru; Antofagasta, Chile; Santiago, Chile; San Diego, California; Bloemfontain, Union of South Africa; and Woomera, Australia. In addition, stations at Mayaguana and Grand Turk Islands will be used as a part of the launching system instrumentation.

The South American stations will be operated by the U. S. Army, which will also provide the communications network for the system. Army personnel are now undergoing training at Blos-

som Point. The Minitrack network will be installed this fall, and it is expected that stations will be calibrated and put into operation by November 1957.

In addition to the prime Minitrack stations, Minitrack Mark II equipment will be used by the Army Map Service to survey some of the islands of the Pacific. The Mark II Minitrack will have a simpler antenna system and a simplified receiving system. It will not be capable of resolving ambiguities in the interferometer output. It is hoped that additional Mark II equipments will be built by groups both in this country and abroad. Information on the Mark II system will be published shortly.

Orbital computations—Data from the Minitrack system will be obtained on every passage of the satellite around the Earth. These data will be sent by teletype to a computing center in Washington, D. C. The satellite orbit will then be computed on the basis of existing data, and a continually improved orbit will be generated as new data are received. Suitable programming of a digital computer for this purpose has been initiated by the Naval Research Laboratory. It is hoped that orbital data will be obtained essentially in real time so that advance information on the expected satellite orbits can be transmitted to the observing stations.

The films obtained from the optical observations will developed on site and rough measurements made. If desirable, these rough measurements will be immediately transmitted by cable or radio to the Smithsonian Observatory at Cambridge. The films will then be mailed to Cambridge where precise measurements will be made. The Smithsonian Observatory has likewise arranged for a digital computer in Cambridge to be used to generate a satellite ephemeris. There will be close coordination between the computing centers at Washington and Cambridge.

As the satellite continues on its orbit, it is expected that the radio data will fail in about two weeks when the batteries are exhausted. Optical data, however, will continue to be received during the entire life of the satellite. Much of the value of the satellite orbital analysis will result from a careful examination of these data extending over many months. In order to provide the fullest opportunity for observers in all parts of the world to utilize the satellite, it is expected that the satellite ephemeris will be published as widely as possible.

The path of the satellite—If the Earth were a completely symmetrical spherical mass, the satellite motion would be an elipse fixed in space except for very slight perturbations caused by the Moon and the Sun. However, because the Earth is an oblate spheroid, the actual motion is considerably perturbed from the simple elipse. Calculations of this perturbation have been made by *Brower* [1946], *Spitzer* [1950], *Davis, Whipple,* and *Zirkner* [1956], and *Blitzer, Weisfeld,* and *Wheelon* [1956]. More recently, L. E. Cunningham in an unpublished note has considered the case of an orbit of any inclination. Figure 8, from Cunningham's paper, gives the result of his calculations. He assumes that the perturbations are due only to the oblateness of the Earth. In Figure 8, the following are used: Ω is the longitude of the ascending node of the satellite's orbit on the Earth's equator; ω is the argument of perigee, that is, the angle in the satellite's orbit from the ascending node to perigee; α_π is the 'right ascension of perigee.' It is the actual right ascension of the perigee point as it would be seen by an observer at the center of the Earth. The heavy vertical line at one degree represents the daily motion of the Sun in right ascension. It is seen that for an inclination of about 39° the daily motions of the Sun and of perigee are equal; consequently, the same point on the satellite's orbit is observable indefinitely in a given twilight zone. It is also noted that the precession rate of the plane of the orbit diminishes as the inclination increases; for an orbit inclined at about 40° to the equator, the period of the precession is about 70 days. It is apparent that measurements of the precession of the plane of the orbit will readily provide a value of the oblateness far more accurate than any now available.

The next most important perturbation to the path is believed to be that due to atmospheric drag. It can be readily shown that a small drag force will be evidenced first by a decrease of the apogee altitude corresponding to the loss of energy due to the frictional resistance. If the perigee altitude is about 200 mi and the apogee about 1000 mi, most of the energy loss will arise from motion of the satellite through the air in the vicinity of perigee. Therefore, the variations in apogee altitude can be interpreted as a meas-

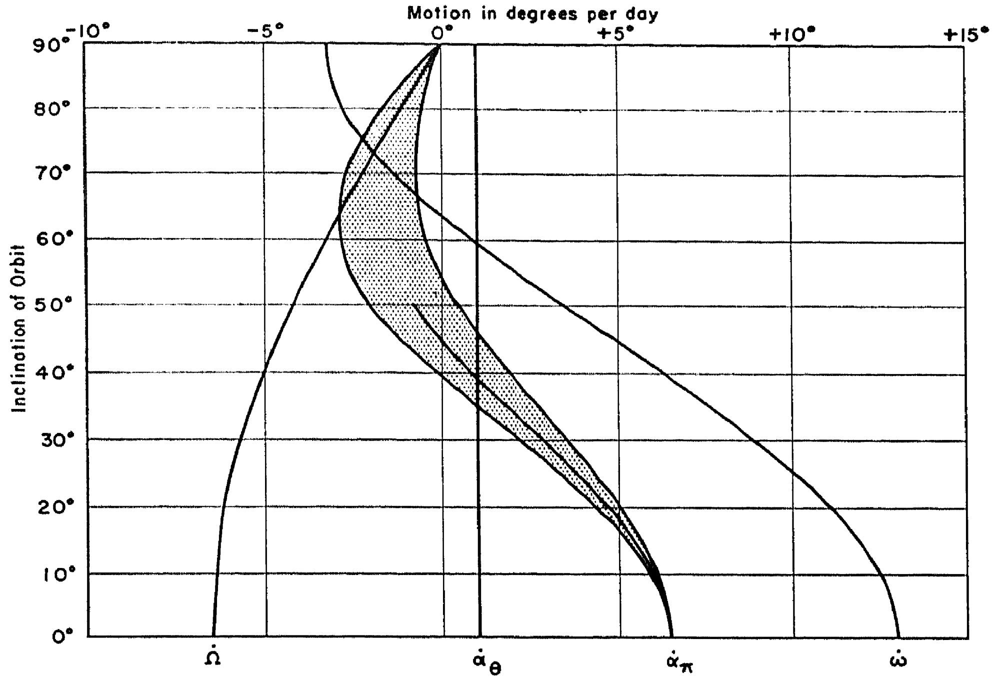

FIG. 8 — Secular perturbations of the orbit for various inclinations (Courtesy Leland E. Cunningham)

ure of the air density near perigee altitude. After the orbit has been reduced to a circle, further loss of energy causes a very rapid decay of the orbit, and the satellite enters the dense atmosphere and is burned up. Calculations of the air density based on the loss of energy of the satellite are complicated by the following: (1) Geometrical factors. Since the satellite is spherical with the exception of its antennas, the orientation of the satellite will not cause a significant change in the drag force. (2) The law of motion of molecules striking the satellite is in some question. If the molecules rebound at double the velocity of the object, the drag coefficient will be two. If the molecules stick to the object, the drag coefficient is unity. (3) Because of the ionization of the atmosphere at these altitudes, there will be an additional drag force caused by the fact that the satellite will become charged and will therefore attract additional molecules into its path so that its effective area will be slightly increased (R. Jastrow and C. A. Pearse, private communication). Although these factors complicate density calculations, it remains that orbital data which show the energy loss due to frictional force will result in far more accurate density data than is now available.

The motion of the satellite will be further perturbed to an unknown extent due to irregularities in the gravitational potential around the Earth. These disturbances may evidence themselves as a 'noise' on the orbit. The question of whether analysis of the orbit can provide information on such disturbances in the gravitational potential is exceedingly complex.

The network of satellite observing stations, particularly the optical stations, will be tied together through the satellite orbit to a very high accuracy, perhaps of the order of 50 ft. Such a world-wide geodetic net does not now exist, and it will consequently be of great value in linking together the triangulation networks in various parts of the world.

REFERENCES

BLITZER, L., M. WEISFELD, AND A. D. WHEELON, Perturbations of a satellite's orbit due to the Earth's oblateness, *J. App. Phys.*, **27**, 1141, 1956.

BROWER, D., The motion of a particle with negligible mass under the gravitational attraction of a spheroid, *Astron. J.*, **51**, 223, 1946.

DAVIS, R. J., F. L. WHIPPLE, AND J. B. ZIRKER, The orbit of a small Earth satellite, *Scientific uses of Earth satellites*, Univ. Mich. Press, p. 1, 1956.

RICHTER, H. L., W. F. SAMPSON, AND ROBERTSON STEVENS, Microlock: A minimum weight instrumentation system for a satellite, *Jet Propulsion Lab. External Pub. 376;* also published in *Proc. Nat. Telemetering Conf.*, El Paso, Texas, May 27, 1957.

SPITZER, L., JR., Perturbations of a satellite orbit, *J. Brit. Inter-Plan. Soc.*, **9**, 131, 1950.

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Scientific Instrumentation of Satellites

James A. Van Allen

Introduction—I should like to discuss in this paper the IGY Earth Satellite Program, and especially the portion with which I have been most directly concerned: the experiments using scientific instruments within the satellite itself. The inclusion of such internal instruments makes possible the investigation of a vastly richer field of phenomena than is possible with an essentially inert satellite which is observed by ground tracking stations alone. Moreover, nearly all of the projects designed for eventual practical applications of artificial satellites (for example, reliable long range weather forecasting) depend essentially on observations made with 'on-board' instruments.

Soon after the organization of the Technical Panel on the Earth Satellite Program in the fall of 1955, many of us had the feeling that one of our first responsibilities was to bring to the attention of the scientific community at large the possibilities and opportunities for making observations with internal apparatus. During the past year and a half, a number of us have devoted considerable effort to conducting conferences, to addressing scientific and technical societies, and to writing and publishing articles in an attempt to bring this about.

One of the major steps in this effort occurred in January 1956. The Upper Atmosphere Rocket Research Panel conducted a major symposium with 38 formal papers discussing specific tangible proposals for using small satellites for observations of physical phenomena. The proceedings of this symposium have recently been published in book form and I believe that this is one of the first substantial professional contributions to this field.

Selection of experiments—In January 1956, a Working Group on Internal Instrumentation was established by the USNC Technical Panel on the Earth Satellite Program to deal with all aspects of 'on-board' observing equipment and, in particular, to sift and appraise the numerous proposals which were by then being received.

The members of this working group are M. Ference now with the Ford Motor Company; W. W. Kellogg from the Rand Corporation; Herbert Friedman, Naval Research Laboratory; Lyman Spitzer of Princeton University; L. R. Alldredge of the Johns Hopkins Operations Research Office; R. W. Porter; and myself (as chairman).

Over 30 serious and competent proposals for satellite experiments in various fields have been received. A substantial effort has been devoted to the study and discussion of these proposals because, as everyone realizes, the possibilities for important and far-reaching research using artificial earth satellites far exceed the limits of the pioneering IGY effort. First of all, we have stringent limitations of technical feasibility in any one flight. Second, we are limited by the number of flights which will be made. And of course, we are further limited by the factor of success which must be applied to any single satellite launching attempt. As a consequence, the selection of the best experiments from among the large number of proposals has been the primary task of this working group.

We have submitted each proposed experiment to four test questions or four test criteria. First, we have undertaken to assess the scientific importance of the proposal. This does not mean we have regarded ourselves as omniscient in deciding whether ionospheric physics is more important than, say, solar physics. We have undertaken no such appraisal whatever. Rather, the point of view has been: Is the proposed experiment, if successfully carried out, likely to yield observations which will significantly aid the understanding of a fairly large body of phenomena and, secondly, does it appear to have the potential for significant discoveries in this field of physics? Although these are matters on which there is seldom unanimous agreement in any diverse group, there has been a strong measure of agreement on these criteria in assessing individual experiments.

The second test question has to do with technical feasibility. This must take into account the weight of the apparatus, the power drain required, the feasibility of storage and transmission of the observed data, and a great miscellany of other technical questions (such as mechanical

ruggedness or proper operation over a large and uncertain range of temperature). In this area the best guidance has come from our experience in the conduct of experiments with rockets during the past decade. Such experience has provided the most tangible technical and scientific foundation for the discussion of satellite possibilities.

Thirdly, we have considered the competence of the group or agency making each proposal, basing this consideration primarily on the previous record of achievement in the general area involved.

Finally, we have put a test question something of this sort: Is the satellite essential to this observation? Does it provide only a moderate increase in effectiveness or does it provide an effectiveness which is enormously beyond that of any other conceivable method?

During the period in which we have been in operation as a Working Group we have sifted and resifted proposals as they have come in; we have asked for and received expert opinion from all available sources; we have had extensive personal presentations by the proposers; and we have undertaken to keep our appraisals both up to date and realistic in accordance with the way in which projects have developed. As a result of this process we have established a hard-core program of on-board experiments. These experiments encompass the following scientific fields: meteorology, geomagnetism, ionospheric physics, cosmic rays, meteorites, and astrophysics. All of these proposed experiments are intimately related to the very extensive programs of ground observations which are being conducted throughout the world during the International Geophysical Year period.

In encouraging projects and in our recommendations for funding, we have had in mind also the longer range national future in this field of scientific endeavor. A further factor has been the possibility of unanticipated difficulties in any one of the hard-core projects. Hence, we have also sponsored certain other developments which have not appeared to be immediately available, but which contribute significantly to the development of a broad competence in this area.

Satellite experiments—Four projects were selected to constitute the hard-core program.

The first is the solar ultraviolet intensity experiment, which uses a basically simple system. As you will see, all of the experiments chosen are basically simple. In fact, in a certain way of looking at it, they are almost ridiculously simple in terms of the preparation which is required to accomplish them. The ultraviolet apparatus consists essentially of only a selective wave length ionization chamber covering the range of about 1100 to 1400 Angstroms. This is a scheme which has been worked out and very successfully used by Friedman at the Naval Research Laboratory in a number of rocket flights during the past several years. Its special scientific interest is in monitoring the intensity of the Lyman alpha line (1215.7 Angstroms) which is the sole significant source of energy from the Sun in the wave-length region between 1100 and 1400 Angstroms. This radiation from the Sun has a profound effect on the Earth's upper atmosphere, by which it is completely absorbed, and exerts a controlling influence on long range radio communications, and possibly on climatic trends. The apparatus planned for a satellite will observe the intensity of this radiation, its fluctuations and the correlation of these fluctuations with related terrestrial conditions. No such continuous observations over an extended period of time have ever been possible before. In addition to this primary experiment (package I), there is a group of so-called environmental experiments being prepared by the Naval Research Laboratory. These have to do partly with matters of engineering in determining for the first time the actual physical conditions of a satellite in flight: measurements of temperature at various points within the body, measurement of the hail of micrometeorites whose magnitude is quite unknown at the present time, and measurements of the erosion of a test patch on the surface of the satellite.

The second experiment is one having to do with the monitoring, measurement and observation of cosmic-ray intensity above the atmosphere over as large a geographical area as possible. My students and I are preparing this experiment at the University of Iowa. The instrumentation consists of a single Geiger tube whose counting rate is electronically stored and read out on passage over the meridian fence of radio tracking stations. In this experiment it is vital that the data be stored for all positions around the orbit; in this way we hope to obtain, for the first

time, a comprehensive geographical survey of the total primary cosmic-ray intensity within a satellite's orbit band width. It is therefore necessary not only to transmit data upon passage through the prime-measurement meridian but to store the data and to know at what point in space it was observed. This requires a precision internal time standard so that when the data are read out we know at which point in space a given counting rate occurred. Interpretation of these data will reveal the geographical symmetry of intensity and the deviations of this symmetry from that of the geomagnetic field. These deviations of symmetry are a sensitive measure of the magnetic fields surrounding the Earth.

In addition to this, we will have, for the first time, the ideal observatory for observing fluctuations of intensity of primary cosmic rays. As you know, there are a large number of IGY monitors distributed around the world. Some of them are in operation already. They are studying the fluctuations of neutron intensity in stations at low altitudes. The IGY period of high solar activity will be an especially fruitful one for the conduct of satellite flights. It is almost certain (I think that I can say it is certain) that successful satellite observations will provide an enormous advance in this scientific field. New theory, or extension of existing theory, is necessary for the interpretation of these experiments. This work is well advanced. There will also be included in package II sensitive gages on the outer skin of the satellite for measuring erosion due to meteoric impacts. These gages are being prepared by E. Manring of the Air Force Cambridge Research Center, Geophysics Research Directorate.

The third experiment comprises extensive measurements of the Earth's magnetic field at high altitudes and over an extended geographical region. The instrument to be used is called a proton precessional magnetometer. This is a new instrument developed by M. Packard and R. Varian of the Varian Associates, Inc., in Palo Alto, California. This device is one of the most important new developments in geophysical instrumentation during the post-war period. It is uniquely suited for satellite work. Comprehensive observations of the total scalar magnitude of the Earth's magnetic field and especially of its fluctuations by these means should lead to an entirely new level of understanding of the nature of the Earth's upper atmosphere and of its astronomical environment. J. P. Heppner of the Naval Research Laboratory is responsible for the overall assembly of this package III and for the interpretation of the observations. I may remark at this point that both the solar ultraviolet and cosmic-ray experiments rest on very extensive and successful rocket experience. The magnetometer experiment is now being subjected to extensive rocket tests by a group of us at the University of Iowa and by a separate group at the Naval Research Laboratory.

In addition to the magnetometer, package III will carry a 30-inch inflatable sphere developed by W. J. O'Sullivan and his colleagues of the National Advisory Committee for Aeronautics (NACA). This sphere together with its container and separable inflation tank weighs less than 0.7 pound. Ground observations of the NACA sphere will provide a sensitive and hence rapid method of determining the density of the Earth's atmosphere at altitudes far above those of any previous experiment. Because of its light weight, the inflatable sphere will be some 200 times as sensitive to air drag as will the parent satellite.

Since the initiation of the satellite program, we have been seeking a meteorological experiment which has the necessary technical simplicity and the fundamental and far-reaching potential for comprehensive study of the world's weather. Two such meteorological experiments are now being developed for package IV. The first was proposed by Harry Wexler of the U. S. Weather Bureau. The equipment is being developed by V. E. Suomi of the University of Wisconsin.

The basic idea of this experiment is to measure the variations of the heat balance over the tropical belt of the Earth. Suomi plans to mount four special temperature-sensing elements at symmetrical points on rods extended from the satellite. These sensors will be titanium spheres about the size of ping pong balls and will be coated with materials sensitive to radiation of various wave lengths. One ball will be as nearly black as possible throughout the range of wave lengths of interest which include the Earth's infrared emission, the solar visible and the reflected solar visible. Another will be relatively black in the visible range and relatively white in the infrared. The third will be relatively white in the visible range and black in the

infrared. Suomi proposes to use as the fourth sensor a 'wave trap,' a device which is sensitive to direction; thus the effect of solar radiation in a directional beam can be distinguished from the diffuse radiation. Point-by-point data on the equilibrium temperatures of the four sensors will provide the necessary data for comprehensive determination of the radiative energy balance of the Earth.

The other meteorological experiment is being developed by W. G. Stroud of the U. S. Army Signal Engineering Laboratories. This experiment is an alternate for package IV and consists of a system for gathering synoptic data on the cloud cover of the Earth within the latitude belt covered by the satellite. The essential elements are two photoelectric telescopes whose lines of sight sweep across the Earth and its lower atmosphere as the satellite spins on its axis. The overall result of these observations can best be described as resembling a sequence of coarse detailed pictures of vast areas of the Earth obtained in succession as the satellite moves along its orbit. Land masses, ocean areas, and cloud formations will be distinguishable. This type of information will be of great value for observation of hurricanes, typhoons and broad weather trends. During the period that a satellite can observe and transmit this type of data vastly more accurate short-time weather forecasting will be possible.

Back-up experiments—In addition to the four primary projects, there are six other proposals for on-board experiments which have been recommended. The support of these other projects is provided in the sense I mentioned earlier, namely, as a general reservoir of possibilities: first of all, to insure against failure of any of the primary list; secondly, to provide for the possibility of further opportunities for flights during the IGY; and finally to contribute to the longer range national competence in this field of research.

The first of these six back-up experiments is a proposal for detecting extreme ultraviolet solar radiation. This experiment was submitted by H. E. Hinteregger of the Air Force Cambridge Research Center. This same organization has sponsored another proposal by Maurice Dubin for relatively detailed meteoric measurements. This latter experiment was brought to an advanced stage of development before the investigators were asked to reorientate their project to a light weight erosion experiment for inclusion in satellite package II.

W. W. Berning and N. W. Arnold of the Army's Ballistics Research Laboratories have been working on methods for determining the electron density at the satellite altitude, a physical quantity of very great interest in ionospheric physics.

Measurement of accumulated meteoric erosion is possible by a technique developed by S. F. Singer of the University of Maryland. This technique utilizes a radioactive material on the surface of the satellite and measures the diminution of the counting rate as the material is eroded away by impact with meteoric dust.

Finally, there are two additional proposals for cosmic-ray measurements. One of these was proposed jointly by G. Groetzinger of the Research Institute for Advanced Studies, Inc., and M. A. Pomerantz of the Bartol Research Foundation. Groetzinger and Pomerantz are developing equipment to determine the intensity of primary cosmic-ray nuclei of heavy elements and the fluctuations of this intensity. The other cosmic-ray experiment has been proposed by H. V. Neher of the California Institute of Technology. This experiment proposes to make cosmic-ray measurements similar to those of package II, except that an ionization chamber is to be used rather than a Geiger tube. A second part of this proposal comprises an experiment of W. A. Baum, also of the California Institute of Technology, for measuring the integrated light coming from different parts of the extraterrestrial sky. The extragalactic part of this light is much weaker than the airglow, zodiacal light, and light from our own galaxy. Although measurements at the Earth's surface are incapable of making the distinction between the extragalactic and other forms of extraterrestrial light, there is a reasonable chance that this separation can be made by measurements from a satellite which is above the atmosphere for a substantial length of time. These measurements, if successful, should distinguish between various cosmological models of our physical universe.

I have, finally, two other comments to make. One is that an orbit of the presently planned inclination, namely about 35° to the geographic

equator, is much too flat for many classes of experiments. A flat orbit does not enable us to penetrate the auroral zone. There is a rich field for satellite observations in the auroral zone, which we are unable to undertake at the present time.

Second, on the subject of the lifetime of the experiments, the general plan of experiments so far has been to use chemical batteries in the interests of proved reliability. If additional studies, and especially the first successful flight, enable us to conclude that the lifetime of our IGY satellites will be as much as six months or more, then there will certainly be a very great demand for the inclusion of solar batteries as the basic source of energy in the apparatus. Much work has already been carried on in this country in the development of solar batteries. The problem, for us, is to adapt these batteries to meet our very rigorous weight requirements; work on this problem has been going on, most notably at the Army Signal Engineering Laboratories, and I am confident that it will be successful. Success in this field will permit extension of the duration of observations with the 'on-board' experiments limited only by the lifetime of electronic components and by the flight life of the vehicle.

Department of Physics, State University of Iowa, Iowa City, Iowa

Sun, Sea, and Air: IGY Studies of the Heat and Water Budget of the Earth *

Roger R. Revelle

The great saga of the Norse kings, the *Heimskringla,* begins with the words "Earth's round face, whereon mankind dwells." The Vikings, like other primitive peoples, thought of Earth as their home and of themselves as its creatures. Today we know that Earth is the only planet of our solar system on which human life could have developed, for no other satellite of our Sun has land masses surrounded by an ocean of liquid water or an atmosphere containing abundant free oxygen.

Our bodies are made up almost entirely of four elements drawn from sea water and air: hydrogen, carbon, oxygen, and nitrogen. The narrow temperature range in which we can survive is maintained by the great heat capacity of the sea and the atmosphere. The waste products that otherwise would suffocate us are continuously dispersed by the easy motions of the atmosphere. We can exist as land animals only because the Sun's deadly ultraviolet and x-rays are fended off by the protective shield of the air, and because the great natural engine of the sea and the atmosphere pumps water continuously from the sea surface and pours it gently down upon the land.

Yet from our point of view, the Earth is a careless mother. Large areas of her surface are too hot or too cold, too dry or too wet to support any large number of human beings. Moreover, she is unreliable. Areas where there was once sufficient water for men to build civilizations are now so dry that only a few desperate nomads can live in them. Elsewhere, a mile-thick blanket of ice has crept down and obliterated once green farms and forests. Millions of our species suffer when a slight change in the running of the sea-atmosphere engine causes drought or flood. Sometimes the engine runs with unpleasant violence. Then thunder storms and hurricanes, tornadoes and typhoons bring destruction and death to many of us.

Because of our dependence on events taking place in the air, almost everyone is an amateur meteorologist. Wherever two or more people are gathered together the first topic of conversation is the weather, and this was probably just as true in the time of Hammurabi or Amenhotep as it is today. Professional weathermen are a new development, however, and it has only been within the last few decades that we have begun to gain an understanding of the great interrelated mechanisms of the air and the oceans.

We know that the sun pours a flood of particles and visible and invisible light into the top of our atmosphere. The amount of visible light appears to be nearly constant, but the intensity of ultraviolet and x-rays and the number of particles varies by at least a hundred-fold [*Chapman,* 1956, p. 19]. The particles are chiefly electrons and protons. The average number of hydrogen nuclei entering our atmosphere is surprisingly large, perhaps a billion per square centimeter per second. During the geological lifetime of the Earth, if all this hydrogen were combined with oxygen as water, it would correspond to a layer over the ocean about twenty meters thick. The energy carried to the Earth by these particles from the Sun during periods of sunspot activity may be as much as one tenth of the total energy of sunlight [*Chapman,* 1956, p. 17].

In addition to particles of ordinary hydrogen, there is new evidence that most of the tritium or radioactive hydrogen on Earth also comes from the Sun [*Craig,* 1956, p. 1125]. It was formerly thought that all the tritium was produced by cosmic rays bombarding nitrogen and oxygen molecules in the upper air, but recent calculations indicate that the amount present is nearly ten times too large to be produced in this way.

The marked variations in ultraviolet radiation and in the number of particles coming from the Sun cause large variations in the temperature and in the electrical and magnetic behavior of the upper atmosphere, because there is such a small amount of air at these high levels. Neither the majority of particles nor the ultraviolet rays penetrate very deeply, however, and

* Contribution from the Scripps Institution of Oceanography, New Series.

it is not clear whether the variations in the amounts coming from the Sun have appreciable effects near the Earth's surface. Visible light is the dominant form of solar energy entering the lower atmosphere. Part of this light is reflected back to space, chiefly from the surface of clouds, snow, and ice. Most of it is absorbed in the atmosphere and the sea, from which it is ultimately re-radiated as infrared radiation.

In this respect, the atmosphere behaves much like the glass in a greenhouse. It easily transmits visible light but is rather opaque to the infrared or heat radiation coming from the ground and the sea surface. Just as in a greenhouse, the air temperature must be considerably warmer than it would be in the absence of materials that absorb infrared, in order to allow a balance between incoming and outgoing radiation. In the greenhouse the absorbing material is the glass roof. The corresponding materials in the atmosphere are three substances present in quite minor amounts: water vapor, carbon dioxide, and ozone.

The temperatures in the upper air do not vary markedly with latitude and consequently the amount of back radiation is roughly the same all over the globe. But the amount of incoming sunlight is greater in the tropics than in high latitudes. As a consequence, air and water warmed in the tropics must move toward the poles. Part of the energy received from the Sun is thus used to carry the excess heat absorbed in low latitudes to high latitudes where it can be re-radiated. The amount of heat transported across the parallels of 30° is 10 to 20 pct of the total incoming radiation [*Starr* and *White,* 1954], but the mechanical work involved is less than one per cent [*Starr,* 1948, p. 193].

The situation can be thought of as if the sea and the atmosphere were interlinked heat engines of very low efficiency. These engines do mechanical work against friction by carrying the working fluids, sea water and air, from the 'firebox' of the tropics to the radiation-cooled 'condenser' of the polar regions. The circulation of the working fluids is manifest in the winds of the air and the currents of the sea. In the atmosphere, it takes place through the coupling of rotary current patterns of all possible shapes and sizes. These include the trade-wind cells of ocean-wide dimensions, the large scale high and low pressure areas of mid-latitudes, the wavelike jet stream, hurricanes, tornadoes, tiny whirls and vortices. In the sea, major units of the circulation include the Gulf Stream and the Kuroshio, the fast moving equatorial currents and the sluggish currents of the abyssal depths. These circulation patterns are partly unstable, and this shows itself to those of us who live in mid-latitudes as the radical changes in weather with which we are all familiar. In low latitudes over the ocean the instability produces the terrifying hurricanes of the western Pacific and of our own east coast.

The behavior of the interlinked heat engines of the sea and the atmosphere is profoundly influenced by four facts: first is their peculiar shape; they are essentially two thin sheets wrapped around a sphere; second, the sphere is rotating; the lower layers of air are dragged along by the rotation, and the movements of both the sea and the air are largely determined by the forces generated by the rotation (at a height above our heads of several hundred miles there is a transition to a zone where the sparse atoms of gas no longer move around the Earth's axis); third, the ocean is not a continuous sheet like the atmosphere, but is broken up by the relatively dry areas we call continents; fourth, like an invisible *pousse café,* the atmosphere is stratified in thin layers that do not mix readily with each other and each of these layers has to a considerable extent a separate behavior of its own. The same is true of the ocean but with the marked difference that while the temperatures of the different layers of the atmosphere are alternatively lower and higher as we go upward, the temperature of the ocean decreases continuously nearly to the freezing point at great depths. It increases slightly near the bottom because of the heat coming from the interior of the Earth.

The energy needed to drive the sea-air circulation is only a small portion of the incoming solar radiation, but it is still enormous on a human scale. The winds of the Earth have a total kinetic energy estimated to equal seven million atomic bombs, or more electric power than all the power plants in the United States could produce in a hundred years. This energy must be replenished every nine to twelve days because of the loss by friction between the winds and the Earth's surface [*Wexler,* 1955].

Although there is general agreement about the foregoing generalizations, our mental model of the sea-atmosphere system is so inadequate in

many essentials that meteorologists are unable to predict anything very useful for more than a few days in advance about the circulation of the atmosphere.

Even more fundamentally, we do not know the factors that determine the average conditions. Consequently, we are quite unable to forecast changes in climate. Yet we know that such changes have occurred in the relatively recent past. Only about ten thousand years ago the Earth emerged from a dark age of snow and ice; less than five thousand years ago, Greenland offered a fair and pleasant habitation for human beings. Within the last fifty years, the climate over eastern North America and northern Europe has again become slightly warmer and the Arctic waters are perhaps again becoming accessible to human beings, while elsewhere prolonged droughts are destroying the work and hopes of decades. For the farmer, the strategist and the statesman, an accurate forecast of climatic change over the next fifty years would be of immeasurable value. But such a forecast is completely beyond our present ability. Ability to forecast depends on understanding, and this comes in two interrelated ways: by constructing small models in our heads of the two great Earth fluids, and by testing and refining these models through observations. This second method is one of the major objectives of the International Geophysical Year. In particular, we are concerned with measurements in areas that have never been adequately explored and of phenomena that have never been adequately studied.

To increase our understanding of climatic change we can ask first, what changes have occurred in the past and how did they happen? Second, because a change in climate is essentially a change of average air temperature, we need to examine the ways in which the heat content of the air can vary. The heat content must be that required to give a balance between incoming and outgoing radiation, hence it can vary if there is a change in the amount of incoming radiation from the Sun, in the proportion of sunlight reflected versus that absorbed, or in the amount of the infrared back radiation absorbed by carbon dioxide, water vapor and ozone. A change of one per cent in the intensity of the incoming sunlight or in the amount of sunlight reflected back to space would give about a one degree centigrade change in the average air temperature [*Plass,* 1956, p. 141].

The total solar radiation seems to be remarkably constant. The most recent continuous observations are those made at the Lowell Observatory since 1953 [*Evans,* 1956, p. 2]. During this period of sunspot minimum no solar variations in the blue region of the spectrum greater than 0.3 pct have occurred. Ionospheric observations show, however, that ultraviolet components of the solar radiation are larger during periods of sunspot maxima and the visual spectrum observations must therefore be continued throughout at least one sunspot cycle before we can say definitely that solar radiation is virtually constant over decades.

In contrast to the apparent constancy of the incoming radiation, the reflectivity of the Earth would appear to be easily changeable. Clouds, snow, and ice reflect most of the sunlight that fails on them, whereas the ocean surface, vegetation and bare ground are highly absorbing for visible light. At present about 50 pct of the earth's surface is normally covered with clouds, while large areas are capped with snow and ice, particularly during winter. An average of 36 pct of the incoming sunlight is reflected back to space without being absorbed [*Danjon,* 1954, p. 734; *Byers,* 1954, p. 303]. The average air temperature would decrease by one degree centigrade if the reflection increased to 37 pct through increased cloudiness or a spreading of the snow- and ice-covered areas [*Wexler,* 1956, p. 488].

Dust in the upper air also scatters and reflects sunlight before it can reach the ground and ocean surfaces. After the explosion of the Volcano Krakatoa in 1883, the incoming radiation from Sun and sky decreased by five to ten per cent for three years [*Wexler,* 1956, p. 485]. Changes in the water vapor, ozone, or carbon dioxide content of the air change the amount and character of the infrared absorption. Calculations by *Plass* [1956, p. 141] indicate that a 25 per cent change in the carbon dioxide content of the air would change the average air temperature by roughly one degree centigrade.

The factors affecting the average air temperature are interrelated; there are in fact what electronic engineers call 'feedback' relationships between them. These feedback linkages are both positive and negative. For example, an increase of air temperature from whatever cause would result in a melting of part of the snow and ice cover of the Earth and a corresponding reduc-

tion in the reflection. Consequently, the amount of absorbed radiation would increase and the temperature would rise still further. This is a positive feedback. Similarly, an increase of average air temperature would increase the evaporation from the oceans, hence the water-vapor content of the air and the absorption of infrared radiation. The temperature would not increase without limit, however, because an increase in evaporation must eventually result in an increase of cloudiness as the water vapor condenses, hence an increase in the proportion of reflected sunlight. This is a negative feedback. Such complex feedback linkages tend to hunt or oscillate, with time constants determined by the speed of the different processes involved.

Thus far we have been discussing comparatively small changes in average air temperature over the Earth. Such changes may be of great significance; it is generally estimated by meteorologists that a four-degree drop in average air temperature would be sufficient to bring on a new ice age [*Wexler*, 1956, p. 488; *Wundt*, 1933, p. 241]. But with present meteorological observing facilities they would be almost impossible to measure. What is observed are local changes of much greater magnitude. These must be brought about chiefly by variations in atmospheric and perhaps oceanic circulation, specifically in the locations of north-south transport of heat and matter.

For example, the January mean temperature at Spitzbergen increased by 24° from 1913 to 1937, whereas during almost the same period there was a three- to five-degree drop in January mean temperature in the Great Basin of the western United States [*Wexler*, 1956, p. 485].

Because of the complex relationship between the amounts of insolation and infrared absorption on the one hand and the circulation patterns of north-south transport on the other, it is by no means certain whether an increase of insolation or absorption would bring on a colder or a warmer climate.

The circulation patterns are profoundly affected by the distribution of continents and oceans, and therefore it is of great importance to make comparative studies of past climatic changes in the northern and southern hemispheres, because of their markedly different patterns of sea and land. Since changes in the intensity of the north-south circulation should have different effects in high and low latitudes, it is also necessary to attempt to determine the nature of simultaneous climatic changes in different latitude zones.

The great ice caps of Antarctica and Greenland and the mountain glaciers throughout the world are remarkable indicators of climatic change. During periods of warming or reduced precipitation the glaciers retreat; when the atmosphere is cooled or snowfall increases, they thicken and rapidly advance. Moreover, the layers of ice laid down in successive years constitute an unrivalled record of events on Earth during past millenia.

Many aspects of glaciers will be studied during the IGY. Among the most significant from the standpoint of the heat and water budget of the Earth will be the thickness of the ice. This will be measured by the seismic techniques used in prospecting for oil. Bore holes and cores will also be taken to study the frozen record of the past.

Ice caps now cover about three per cent of the Earth's surface. A melting of two feet per year over these surfaces seems quite possible from present data. This would result in a rise of sea level of about an inch per year or roughly ten feet in one hundred years. Even such a rise as this would bring serious consequences to many thickly populated coastal areas.

The sediments of the deep-sea floor, like the ice caps, contain a detailed climatic record extending back over many thousands of years. For example, variations in the numbers of limy shells of the tiny animals called foraminifera reflect variations in the oceanic circulation near the surface. The ratios of oxygen isotopes in these shells tell us something about past ocean temperatures. At least part of the present temperature differences we can measure between different layers in deep-sea sediments may be the result not of heat flow from the Earth's interior but of warmer temperature of the deep ocean waters a few hundreds or thousands of years ago. Studies of these sediments and their significance for climatic change will be an important part of the series of oceanographic expeditions to be conducted during the International Geophysical Year.

The meteorologist and the oceanographer can seldom use that peerless tool of the laboratory scientists, the controlled experiment. As substitutes for experiment they must attempt to make comparative investigations of the behavior of

the Earth fluids under different conditions. For this reason a major part of the IGY meteorological program will be focussed on comparisons between the southern and the northern hemispheres.

Because the Earth is closer to the Sun in January than in July, the southern hemisphere receives about six per cent more radiation in summer than does the northern. The geometry of the two hemispheres is also quite different. In the north, the polar sea with its thin, cracked skin of ice is surrounded by continents; in the south a continent nearly twice the size of the United States, having an ice-covered surface two miles above sea level, lies at the pole and is surrounded by the great southern ocean. This high central plateau, sheathed in darkness for six months each year, is a focal point for inward-circling storms and outward surges of cold air. The weather conditions in the Antarctic are nearly incredible; for example, wind velocities at Adelie land have averaged 110 mi/hr for a day, more than 60 mi/hr for a month and about 40 mi/hr for an entire year. The American IGY party now maintaining a vigil at the South Pole have already recorded temperatures below $-100°F$ with 15- to 20-knot winds.

As is well known, the testing of large atomic weapons produces considerable amounts of radioactive substances, some of which decay rather slowly. A large part of the radioactive material produced by atomic weapons tests is injected into the upper strata of the air and can be used by meteorologists as a tracer of atmospheric movements, for example to determine the rate at which the air at different levels is carried from the northern to the southern hemisphere and vice versa, and the rate of mixing between the upper and the lower atmosphere. An important IGY objective will be world-wide measurements of these artificially radioactive substances.

A slight excess or deficit in the input of solar energy over the output of infrared radiation from the Earth may cause large changes in weather and, if long continued, in climate. At present we are unable to determine whether such differences between income and outgo exist. Here the Earth satellite program shows great promise; one of the first satellites will carry relatively simple equipment for measuring the difference between the amounts of incoming and outgoing radiation at all points over its path [*Wexler,* 1957, p. 144]. Later satellite experiments will include actual mapping of the Earth's cloud and snow cover, allowing accurate and continuous measurements of the amount of sunlight reflected from the Earth, a quantity that can at present only be rather crudely estimated.

A change in average air temperature represents, of course, a gain or loss of heat from the air, but it need not represent a gain or loss from the ocean-atmosphere-glacier system of the Earth. On the other hand, an excess of heat could be stored for long periods on the Earth without much change in the temperature of the lower air. There are two great mechanisms for this: one is the melting of ice caps, the other is the heating of the deep waters of the ocean. The latter has by far the larger capacity. The energy required to melt all the ice in Antarctica is equivalent to about two and a half years' supply from the Sun reaching the Earth's surface at the present rate of 175,000 cal/cm^2 yr. This same amount of energy would raise the average temperature of the ocean by only a little more than one degree C. (On the other hand, the melting of ice caps would be somewhat more obvious to everyone, since it would result in a rise of sea level by at least 200 ft, and the consequent destruction of most of the world's largest cities!)

Because of the great heat capacity of the ocean, many meteorologists and oceanographers now believe that climatic changes lasting over decades or centuries may be intimately related to changes in the circulation of the deep sea. Effective techniques for studying this circulation have become available only in the last few years, and it is little understood. We know that cold water sinks to great depths from the surface in high latitudes, moves slowly toward the equator and perhaps across it, and returns by an unknown path to the starting point. The time required for the round trip is not known; it may be measured in decades or millenia. Nor do we know whether the circulation is steady, or intermittent like the flushing of water in a bowl.

One of the major enterprises of the International Geophysical Year will be a series of great oceanographic expeditions, conducted by 70 ships belonging to many countries. Their principal objective will be to obtain a comprehensive picture of the temperature and other properties of the deep sea waters, and to make direct and indirect measurements of their motions.

President Eisenhower has said that water is rapidly becoming our most critical natural resource. During the last few years, serious attempts have been made to develop inexpensive machines for converting sea water into fresh water. The fact is, of course, that nature herself operates a most effective distillation system. Nearly one-third of all the energy of sunlight falling on the sea surface is utilized in converting sea water to fresh water by evaporation. The immense quantity of solar power used in this way is several thousand times all the power produced by our industrial society from hydroelectric power and the burning of coal, oil, and natural gas.

The total quantity of water evaporated, if all of it fell on the surface of the land and were uniformly distributed, would result in an average rainfall of over one hundred inches a year. Evidently the trouble with the natural distillation process is not the quantity of fresh water produced, but rather that nature's pipe lines are badly placed. Too much water moves to some areas and not enough to others; moreover, the valve system seems to be capriciously managed. Sometimes the discharge is too great, bringing floods, while at other times there is only a trickle and droughts occur. Can anything be done about this faulty distribution system?

The quantity of solar energy used in driving the engine of the sea and the atmosphere is so great compared to any of the energy sources under man's control that it would seem impossible for us to affect weather or climate materially by any human action. Yet a close look shows there may be some things we could do. Many of the processes in the atmosphere are metastable: a slight action may initiate a very large scale process. We might learn how to regulate climate if we could find the right lever to pull.

One may predict that with the coming of greater understanding promising methods for control of weather and climate will be found. The average reflectivity of the ground surface over large areas might be reduced, for example, by rapid melting of the snow cover, thus increasing the percentage of sunlight absorbed. On the other hand, it might be possible to shut off some of the Sun's radiation before it reaches the Earth's surface, for example, by injecting a small amount of absorbing or reflecting substances into the upper atmosphere.

During our lifetime we may be witnessing an example of one way in which human actions can affect weather and climate. Since the beginning of the industrial revolution, an amount of carbon dioxide equal to about 12 pct of the total already present in the atmosphere has been produced by the burning of coal, oil, and natural gas. The ability of the ocean to absorb carbon dioxide is very great and probably most of the amount added to the atmosphere during the last century has gone into the sea. During the next hundred years, however, the increasing use of fossil fuels in our world-wide industrial civilization should result in the production of about 1700 billion tons of carbon dioxide, 70 pct of the amount now in the atmosphere [*Revelle* and *Suess*, 1957, p. 19]. Because of the rapid increase in the production rate, the fraction of the added carbon dioxide absorbed by the ocean will be lessened and an increase of perhaps 20 pct in atmospheric carbon dioxide can be expected. The effect of such an increase is not easy to predict, but there is some theoretical reason to believe that it could result in a warming of the lower atmosphere by several degrees. Thus by consuming, within a few generations, the fossil fuels laid down in sedimentary rocks over many hundreds of millions of years, we are conducting, more or less in spite of ourselves, a great geophysical experiment. It is of vital importance to keep accurate records of this experiment in order to increase our understanding of the mechanisms controlling climate. With this in mind, careful measurements will be made during the IGY of the carbon dioxide content of the atmosphere, and studies will be initiated to refine our estimates of the absorption of carbon dioxide in the sea.

References

Byers, Horace R., The atmosphere up to 30 kilometers, *The Earth as a Planet*, pp. 299–370, 1954.

Chapman, Sydney, Solar influences on the upper atmosphere, *The Sun's effects on the Earth's atmosphere*, Tech. Rep. 2, High Altitude Obs. Univ. Colorado, pp. 11–20, Oct. 1956.

Craig, Harmon, Distribution, production rate and possible solar origin of natural tritium, *Phys. Rev.*, **105**, 1125–1127, 1957.

Danjon, André, Albedo, color, and polarization of the Earth, *The Earth as a Planet*, pp. 726–738, 1954.

Evans, John W., Variations of the Sun, *The Sun's effects on the Earth's atmosphere*, Tech. Rep. 2, High Altitude Obs. Univ. Colorado, pp. 1–10, Oct. 1956.

PLASS, G. N., The carbon dioxide theory of climatic change, *Tellus*, 8, 140–154, 1956.

REVELLE, R., AND HANS E. SUESS, Carbon dioxide exchange between atmosphere and ocean, and the question of an increase of atmospheric CO_2 during the past decades, *Tellus*, 9, 18–27, 1957.

STARR, V. P., On the production of kinetic energy in the atmosphere, *J. Met.*, 5, 193–196, 1948.

STARR, V. P., AND R. M. WHITE, Balance requirements of the general circulation, *Studies of the atmospheric general circulation*, Mass. Inst. Tech. Final Rep., pt. 1, General Circulation Proj., pp. 186–242, 1954.

WEXLER, HARRY, The circulation of the atmosphere, *Sci. Amer.*, Sep. 1955.

WEXLER, HARRY, Variations in insolation, general circulation and climate, *Tellus*, 8, 480–494, 1956.

WEXLER, HARRY, Meteorology in the International Geophysical Year, *Sci. Mon.*, 84, 141–145, 1957.

WUNDT, W., Änderungen der Erdalbedo während der Eiszeit, *Met. Zs.*, 50, 241–250, 1933.

Scripps Institution of Oceanography, University of California, La Jolla, California

Synoptic Meteorology and the IGY

Morton J. Rubin

Introduction—Of all the basic aids which meteorologists use in their attempts to understand and explain the motions of our atmosphere, the most widely used is the synoptic map. A synoptic map can be many things to many people, but to a meteorologist it is essentially a device used to portray the instantaneous state of the atmosphere, usually at a given level, as regards several basic parameters such as wind, temperature, and humidity, or additional derived parameters such as vorticity. Depending upon the use to which the analysis of these data is to be put, the area represented by one map can vary from several thousand square miles to an entire hemisphere.

Synoptic meteorology in the above sense has been practiced for more than one hundred years, and has served as a convenient and valuable aid to the researcher and to the daily forecaster. That synoptic analysis still is considered to be of value is indicated by the establishment of the IGY World Weather Map Project, which will provide for the preparation of daily synoptic charts for at least two levels in the atmosphere over the entire globe. It is one convenient way by which meteorologists can keep their fingers on the pulse of the constantly changing atmosphere, and chart its large-scale daily variations so as to know where and when to look for developments of importance. The great mass of IGY meteorological data which will be forthcoming from this monumental international effort will be of considerably greater value, and utilization of the data for the benefit of mankind will be more complete because of synoptic analysis.

It is often said that the atmosphere of the Earth operates as one enormous heat engine, in the sense that energy in the form of heat from the Sun is applied essentially in one region, and the resulting temperature gradients cause the large-scale motions of the atmosphere and oceans, thus converting the heat energy into kinetic energy. But this simple concept is far from an adequate explanation of the complicated seasonal and annual manifestations of the general circulation. Great variations occur in the atmospheric circulation, both within a season or a year, and from one season or year to another, because of many as yet unevaluated causes, but probably related to such factors as mechanical turbulence, condensation processes, and changing albedo. Thus the mean circulation cannot be inferred as a consequence of a predetermined pattern of energy input.

For the past two hundred years, since the time of *Hadley* [1735] and his first attempts to describe and explain the basic motions of the atmosphere, meteorologists have had as their number one problem the description and cause of the general atmospheric circulation and its variations. As more and more data have become available through the extension and development of observational techniques and networks, more complete and faithful descriptions of the atmospheric motions have been made possible. A model of the Earth's atmospheric circulation proposed by *Rossby* [1941] is shown in Figure 1. It presents the entire circulation in one unified concept. It has deficiencies, as can be imagined, because of lack of sufficient information, particularly from the high atmosphere. However, it did approximate many of the large-scale features of the atmospheric circulation, as known at that time, and it did stimulate much interest and research activity as new and better data became available.

The IGY, through its emphasis on the expansion of basic observational networks in all the geophysical disciplines, and particularly in meteorology, is giving another great impetus to synoptic studies. Through the use of IGY data,

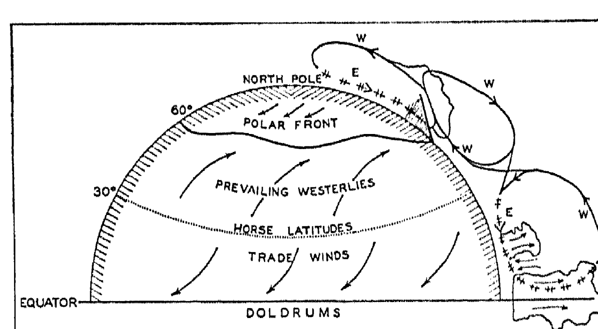

Fig. 1—The cellular meridional circulation on a rotating Earth [*Rossby*, 1941]

we will have an opportunity to fill in our knowledge of the Earth's atmospheric circulation in regions such as Antarctica and the very high levels over much of the world from which scanty data have been available, and where much of our knowledge has been obtained often only by inference. Synoptic meteorology will be the first of the beneficiaries of the IGY effort. The southern hemisphere countries are already benefiting from the expanded networks in that hemisphere, particularly through the new networks in Antarctica and South America, which are operating for the first time in history. We know that it is almost always necessary to describe a phenomenon or process before we can hope to understand it. And this is what synoptic meteorology has done and will do. Daily, or more frequently, as through the IGY World Weather Map Project, or through the work carried on at any of the meteorological centers in the world where large-scale analysis is carried on, descriptions of the atmospheric motions, and the resulting weather conditions, will be prepared. Using these maps, and from derived parameters, and through calculations of energy exchanges, qualitative and quantitative approximations of the significant characteristics of the atmosphere will be obtained. The relation of these characteristics, or their response to other factors, such as possible changes in emission, transmission and absorption of solar radiant energy will be energetically studied.

Apart from the World Weather Map Project, which will be carried out as a retrospective analysis of IGY data, another milestone in the history of synoptic meteorology has been passed with the establishment of the IGY Antarctic Weather Central. At the present time a group of meteorologists from three participating countries is carrying on a day to day synoptic analysis of meteorological conditions in and around Antarctica. The results of these current analyses are broadcast to all Antarctica and the southern hemisphere to be used in immediate weather studies for forecasting purposes. The result of these analyses will ultimately and inevitably help to make clear the long obscure and often disputed role of the Antarctic continent in the large-scale hemispheric and global circulation patterns.

Throughout most of its history synoptic meteorology has been intimately linked with weather forecasting. That this should be so is not strange, because the practical end result of all knowledge is its application to predictions of future physical states, whether it be in meteorology, medicine, or mechanics. Synoptic meteorology has progressed from what were rather crude representations of a few simple meteorological parameters in only two dimensions over restricted and often discontinuous regions of the Earth, to complex groups of charts showing basic or derived physical parameters in three dimensions over much of the world. But even today many gaps exist, which tend to inhibit the development of meteorological knowledge and frustrate the meteorologist in the application of his accumulated knowledge. New techniques have been developed, first, to obtain more data, as past experience may have pointed out the areas of activity in which more information is necessary, and second, to apply analytical techniques so as to utilize all of the information so obtained. The analyst and the forecaster today are frequently not one and the same person. The multitude of data and the complexity of the processes preclude that one man can adequately fulfill both responsibilities. But we may well ask, why do we want more data if we cannot adequately handle what we now receive? The answer is simple. We are now at a point in meteorological development where we can expect only slow and limited progress unless we can probe the entire mass of the atmosphere and know its complete state. At the present time we are adequately describing about 20 pct of the atmospheric mass. Fortunately, we are also at a stage in our technological development where electronic machines and computers already can perform many of the routine chores of analysis and forecasting which severely try the capacity of the present human analysts and forecasters in respect to actually scrutinizing masses of data. We know that we must have data from all parts of the world, and from everywhere within the atmosphere from sea level to the very upper limits. The machines can cope with the masses of data, and they can even forecast the future state of the atmosphere with reliability approaching that of the human forecaster. As new models of the atmosphere are developed, it is likely that the machine even will be able to outstrip the human. That is all to the good, because it will free the human analyst and fore-

caster from his routine tasks, and allow him to exercise his ingenuity and to apply his knowledge to interpreting the states of the atmosphere in terms of weather, and to devise new and improved methods of analysis to be applied by the machine.

Past experience has shown that, within limits, the longer the period of time for which weather forecasts are to be made, the greater is the area from which current weather data must be available for synoptic analysis. Thus, as greater demands have been made upon the synoptic meteorologist, the greater have been his demands for more and better weather reports. At the present time, the meteorologist who is engaged in forecasting weather as far ahead as five days over a region as large as the United States requires an analysis of the current meteorological situation over the entire northern hemisphere and at several levels in the atmosphere up to as high as 12 km. Even so vast a coverage as this may not be sufficient for longer range forecasts. From the present limited knowledge we have of the atmospheric circulation, it is felt that successful long-range forecasting depends upon an adequate representation of the current state of the atmosphere over the entire world, and from sea level to the level of 80,000–100,000 ft. Such demands are impossible of fulfillment at the moment, so that even the tremendous IGY effort will fall short of the optimum. However, as in the past, each new extension of the scope of our data-collecting facilities has helped us to arrive at a better understanding of the atmospheric processes, and has permitted our guesses to become more educated.

Today the broad features of the global circulation are known to the degree that one can already attempt to make forecasts as far ahead as 30 days with more than a small chance of being reasonably successful. The small-scale features of the atmosphere still appear to us, in our ignorance, often to be random phenomena, and much more awareness of the effects of external influences and the internal mechanism must be obtained before we can hope to solve more than only the simplest of our meteorological problems. But the problems of energy exchanges and transformations, local influences, etc., are vexing only because of our limited knowledge. The way has been shown by the patient researchers who have worked with the limited but ever-increasing data over the past years. The physical principles are known, and the results of analysis of relatively crude data have pointed out the basic features of the planetary circulation, the magnitude of the transports of mass and energy which are thereby effected, and even the role of the secondary circulations, either as influencing the general circulation or being influenced by it. It is inevitable that the lack of complete data has caused different researchers often to come to differing conclusions, but it is also inevitable that as more data become available, and as a more complete representation of the atmospheric circulation becomes possible, these differences will largely disappear.

World weather maps—The World Weather Map Program which will be carried on during the IGY is an extension of several separate projects describing the northern and southern hemisphere circulations. The U. S. Weather Bureau's Northern Hemisphere Historical Series [*McMurray,* 1956] was the first continuing long-term series of daily weather maps which could serve as a basis for research in general circulation. Many of the recent studies have used these maps as the source of data. The U. S. Weather Bureau also instituted a Southern Hemisphere Map Analysis Project in 1948 [*Rubin,* 1952], recognizing that knowledge of the circulation over the entire globe is necessary. This project continued until 1952, and the *South Africa Weather Bureau* [1952], which is now carrying on this work, began its own project in 1951. This has been the first prolonged effort to provide a synoptic map of the southern hemisphere on a daily basis.

Figure 2 is the sea-level synoptic chart of the southern hemisphere for March 19, 1949. The data at that time were nonexistent over Antarctica, and other gaps were present. Now the Antarctic stations are filling the main void, and complete analyses are being carried out at the IGY Antarctic Weather Central. These analyses will be coordinated with the IGY World Weather Map series, as well. Antarctica and its influence on the general circulation will be very carefully scrutinized during the IGY.

A number of circulation studies have used these maps as their source of data. From these studies, and from earlier work based upon a series of monthly mean maps of the world prepared in Brazil [*Serra,* 1948], certain evidence

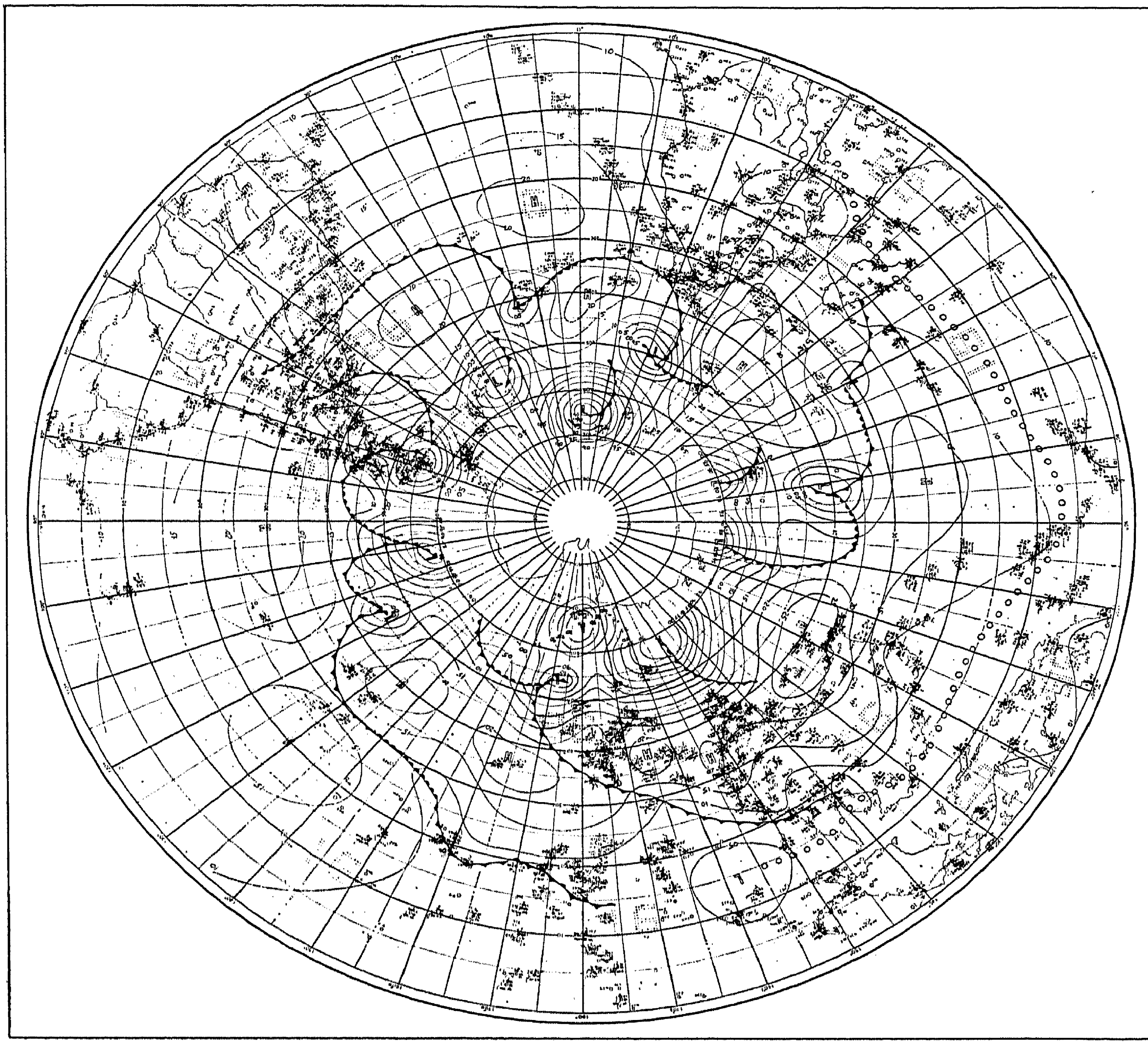

FIG. 2 — The sea level synoptic chart of the southern hemisphere; March 19, 1949

has been presented which indicates that definite relationships exist between the circulations of the two hemispheres. Indeed, it would be strange if they did not exist, for we are, after all, dealing with only one atmospheric system. The IGY World Weather Map Series, which will include a detailed analysis of both hemispheres, and the equatorial regions separately, will be based upon complete IGY data, much of it never available heretofore. It will serve as the basis for new and detailed studies of the general circulation in all its aspects. The three sections, northern hemisphere, southern hemisphere, and equatorial zone, will be prepared on separate maps. The map shown in Figure 3 is the first to depict the surface pressure pattern over practically the entire world. The Gall's stereographic projection used is neither conformal nor equal area, although distortion is minimized in the middle latitudes. The IGY hemispheric maps will be on a polar stereographic projection; the equatorial map will be on a mercator projection. A notable forerunner of the IGY World Weather Map series was a series for 36 days of the International Year 1933, prepared for the International Commission for the Exploration of the Upper Air. They are believed [*Shaw*, 1936] to be the first synchronous charts of pressure for the whole world, although the analysis is lacking for more than half the surface of the world. The IGY maps, however, will be based upon data coverage from almost the entire world,

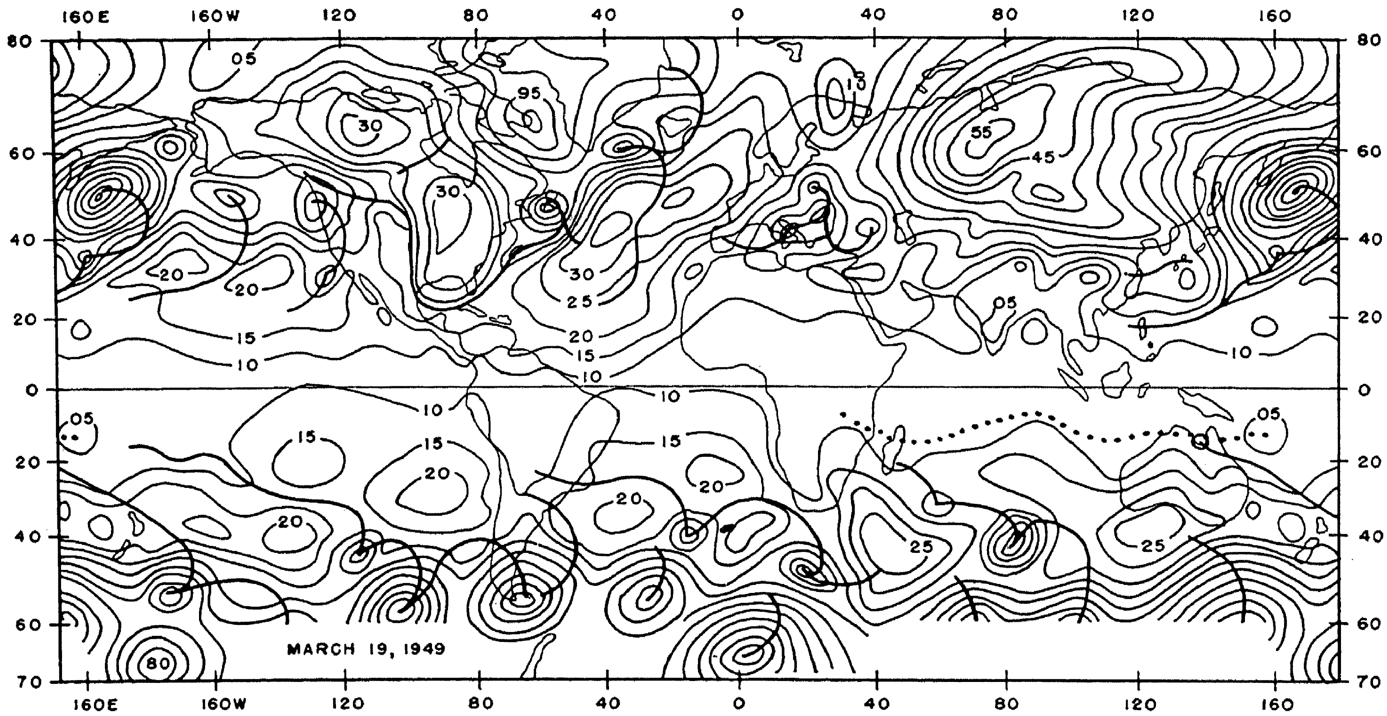

FIG. 3 — The surface synoptic chart of the Earth; March 19, 1949 [*Alpert,* 1952]

including both polar regions. The main deficiencies will exist over the oceans of the southern hemisphere.

Features of the circulation—The analysis of the increasing quantity of upper-air data over the past ten or fifteen years has pointed out several salient features of the general circulation such as the jet stream, middle-latitude waves and disturbances, high-latitude deep cold cyclones, large-scale warm anticyclones, 'polar night stratospheric jet stream,' etc. All of these features are part of the circulation and have to be explained in terms of a unified theory of the atmospheric circulation. Several circulation models have been proposed which attempt to fit the observations, more or less successfully. These circulation models are not new; actually one which is still valid, in its major aspects, was proposed by *Hadley* [1735]. In addition to mathematical-physical models which attempt to explain the mechanism of the general circulation, certain laboratory models have been devised which also reproduce some of the major features of the circulation [*Fultz,* 1951]. Of course, the atmosphere is its own best model, and if we watch it long enough, and probe it often enough, which is what we will be doing during the IGY and afterward, we will arrive at a better understanding of its vagaries. That we do understand its main features and what influences are important over short periods of time up to several days in advance, is attested to by the reasonably good prognoses which can be made by using mathematical-physical models and machine methods.

It is thought by some meteorologists that the main atmospheric motions are caused by or greatly influenced by the processes going on at very high altitudes, those levels at and above 25 km, where the Sun's energy is first absorbed by the atmospheric mass, as in the ozone layer. Despite the fact that only about two per cent of the atmospheric mass exists above the 25-km level, great variations in temperature and circulation have been noted. For instance, at the 20- to 25-km level the temperature over North America has been observed to increase by 50°C, from −70°C to −20°C within one week's time. Synoptic studies of the circulation at these levels are now being carried on, and information so obtained is incorporated into the expanding fund of knowledge of the atmospheric systems. IGY sounding balloons are expected to reach these heights regularly, and give even more data over the entire world in regions where such data have not been available. The rocket program, of which we expect so much, will aid immeasurably in probing the atmosphere to even higher levels, and the data so obtained will help to solve the riddle of these almost 'explosive' warmings.

The two maps shown in Figure 4 depict the

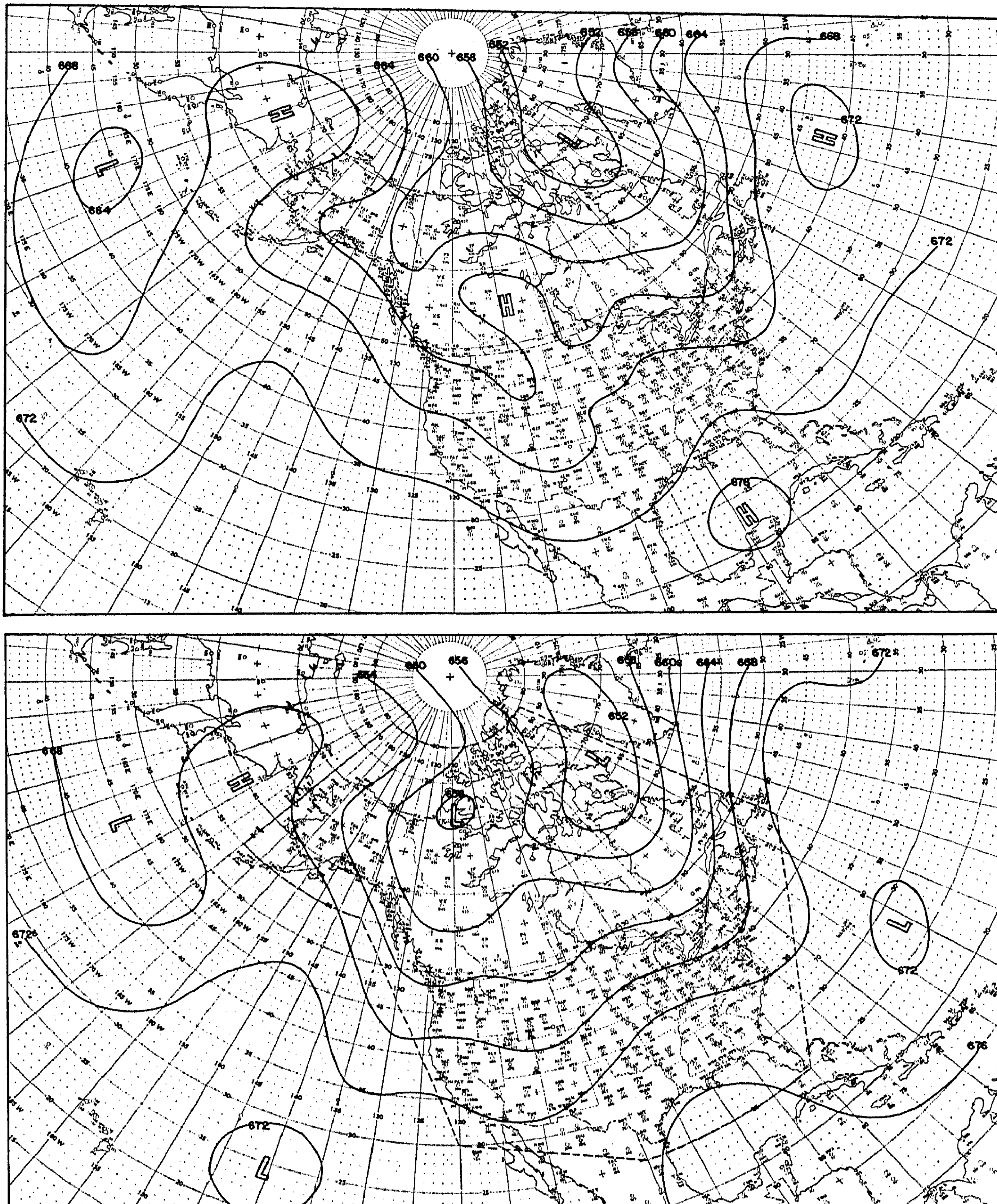

FIG. 4 — 50-mb constant-pressure surface charts over the North American continent at 03h 00m GMT on January 27, 1953; upper chart prepared from actual data, lower chart prepared from USWB data obtained by extrapolation from lower-level data through statistical relationships [*Moreland* and *Cluff*, 1955]

50-mb constant pressure surface over the United States at 03h 00m GMT on January 27, 1953. That it is better to work with real data rather than extrapolated values is apparent in the fictitious smoothing and by the displacement of centers of high and low values on the lower map. The increased data from high levels obtained during the IGY will reduce considerably our dependence upon using extrapolated data for high-level analyses in many parts of the world.

The jet stream, a rather narrow high-speed stream of air imbedded in the atmosphere in long, sweeping, often discontinuous, currents of air encircling the globe at various latitudes, and lying just below the top level of the troposphere (8–10 km), and usually where the strongest horizontal temperature gradients occur, is another atmospheric phenomenon which has attracted much attention. The jet stream seems to be symptomatic of the state of development of the circulation at a given time, and may even be the mechanism whereby essential exchange processes take place. IGY high sounding balloons will help keep track of this phenomenon, and help fit it into a unified concept of the atmospheric circulation.

Meridional sections of the atmosphere have been produced in the past to portray the vertical temperature and wind distribution, usually along one meridian. One of the big efforts during IGY is to maintain four principal sections from North Pole to South Pole. The cross-sections which have been prepared so far, have not been true pole-to-pole sections, and particularly in the southern hemisphere there is doubt as to the representativeness of the few which have been prepared. The four IGY pole-to-pole sections will be more complete and representative. The seasonal, or shorter period shifts of the various belts of activity will be followed closely in order to relate them to other inter- and intra-hemisphere phenomena from these and other sources.

Puzzle of the circulation—In this brief survey of synoptic meteorology and the IGY it has been necessary to omit many of the details of observation and research through which our present concepts of the complicated atmospheric circulations have been developed. We liken these concepts to a partly finished jigsaw puzzle, within whose frame are placed a number of isolated pieces, some of which are joined to others. Some even may be wrongly placed, but we have an idea that several pieces from the jumbled pile outside the frame will fill important gaps, and thereby permit us to fill in the picture. This is what we hope for from the IGY: that enough of the missing gaps will be filled to permit us to complete the puzzle.

References

ALPERT, L., Global weather maps, *Bul. Amer. Meteor. Soc.*, 33, 435–437, 1952.

FULTZ, D., Experimental analogies to atmospheric motions, *Compendium of Meteorology,* Am. Meteor. Soc., Boston, 1235–1248, 1951.

HADLEY, G., Concerning the cause of the general trade winds, *Phil. Trans. R. Soc., London,* 39, 58, 1735.

MCMURRAY, W. M., Data collection for the Northern Hemisphere map series, *Mo. Wea. Rev.,* 84, 219–234, 1956.

MORELAND, W. B., AND F. D. CLUFF, Problems and examples of Northern Hemisphere stratospheric analysis, paper presented at the 136th National Meeting of the American Meteorological Society, Washington, D. C., May 5, 1955.

ROSSBY, C.-G., The scientific basis of modern meteorology, *Climate and Man—Yearbook of Agriculture,* U. S. Department of Agriculture, Washington, D. C., 599–655, 1941.

RUBIN, M. J., Southern Hemisphere synoptic analysis, *Bul. Amer. Meteor. Soc.,* 33, 409–415, 1952.

SERRA, A. B., *Atlas de Meteorologia,* 1873–1909, Serviço de Meteorologia e Conselho Nacional de Geografia, Rio de Janeiro, 1948.

SHAW, N., *Manual of Meteorology,* vol. II, Second Ed., Cambridge, 1936.

SOUTH AFRICA, WEATHER BUREAU, Tables and charts of Southern Hemisphere sea-level pressure, *Notas* 1, 23–64, 1952.

Office of Meteorological Research, U. S. Weather Bureau, Washington, D. C.

U. S. Special Meteorological Studies for the IGY

Sigmund Fritz

Introduction—During the IGY several major categories of special meteorological observations will be made. These include measurements of radiation, atmospheric composition, and nuclear radiation. Under the category of radiation, measurement will be made of the heat budget of the Earth with satellites, and of small portions of the Earth from surface observations. The 'polar whiteout' is a phenomenon involving visible radiation which will be studied. Plans for the category of atmospheric composition, include measurement of total atmospheric ozone and also of surface ozone measurements. Carbon dioxide will also be measured extensively. To study atmospheric radioactivity, measurements will be made at the surface and aloft.

Radiation

Heat budget—The geographic distribution of net radiative energy absorbed by the earth-atmosphere system is one of the major driving forces of the general circulation of the atmosphere. At present, we know this radiative distribution rather poorly. Our uncertainty about this basic radiative regime is shown in Figures 1 and 2 [*Jung*, 1956]. Figure 1 shows some computations of the net radiation for different latitude circles averaged around the Earth. Each of the curves represents the work of a different author. They agree that south of latitude 37° N there is a net heating on the average while north of 37° there is net cooling. We note, however, that at the equator there is a difference of opinion regarding the energy gain by a factor of two, and that in the polar regions the disagreement is even worse. Since except for small changes, the annual mean temperatures are nearly constant at each latitude, the excess heat must be transferred from the equatorial regions to the polar regions. The distribution of the transport of heat required for balance is shown in Figure 2. Here again, we see estimates by various authors, and note as much as a two-fold difference between some of them. And we see further that some of the greatest disagreements occur between the most recent attempts. In other words, we are uncertain about the magnitude of the Earth's radiative heat budget and about the energy transports by atmosphere and ocean which this implies. And moreover, our most recent estimates do not seem to be in better agreement than older attempts.

We need, therefore, a new approach to the investigation of the problem of the world-wide radiative balance. The most appropriate time to intensify our efforts is during the IGY, the period of world-wide geophysical research; the most appropriate vehicle for this world-wide study is the satellite. During IGY, therefore, to supply basic data about the heat budget of our Earth we shall use two satellites: (a) an artificial satellite, and (b) the Moon.

Artificial satellite observations—One of the experiments planned for a Vanguard scientific satellite will be carried out by V. E. Suomi of the University of Wisconsin. He will mount four small spheres on the antennas of the satellite, and coat them with materials of different but known reflectivity. Therefore, when the spheres are subjected to the same radiative fluxes, the sphere temperatures will be different. For example, one sphere will be painted black, while another sphere will be painted white. Both will see the radiation from the Sun and from the Earth. The black sphere will, of course, be warmer than the white one. A measure of the temperatures of three spheres will provide a means for calculating (a) the radiation from the Sun to the Earth, (b) the solar short-wave radiation reflected from the Earth, and (c) the long-wave radiation emitted from the Earth mainly by virtue of its own temperature, moisture, and cloud distribution. This IGY satellite experiment will provide data for tropical latitudes only, but we certainly hope that data for the whole Earth will be available from future satellites.

As Figures 1 and 2 show, at present we are uncertain about the average radiative regime. This we hope to study with the satellite data. But, *a fortiori*, we are even more ignorant now about the change in the radiative distribution from day to day, or month to month, or year to

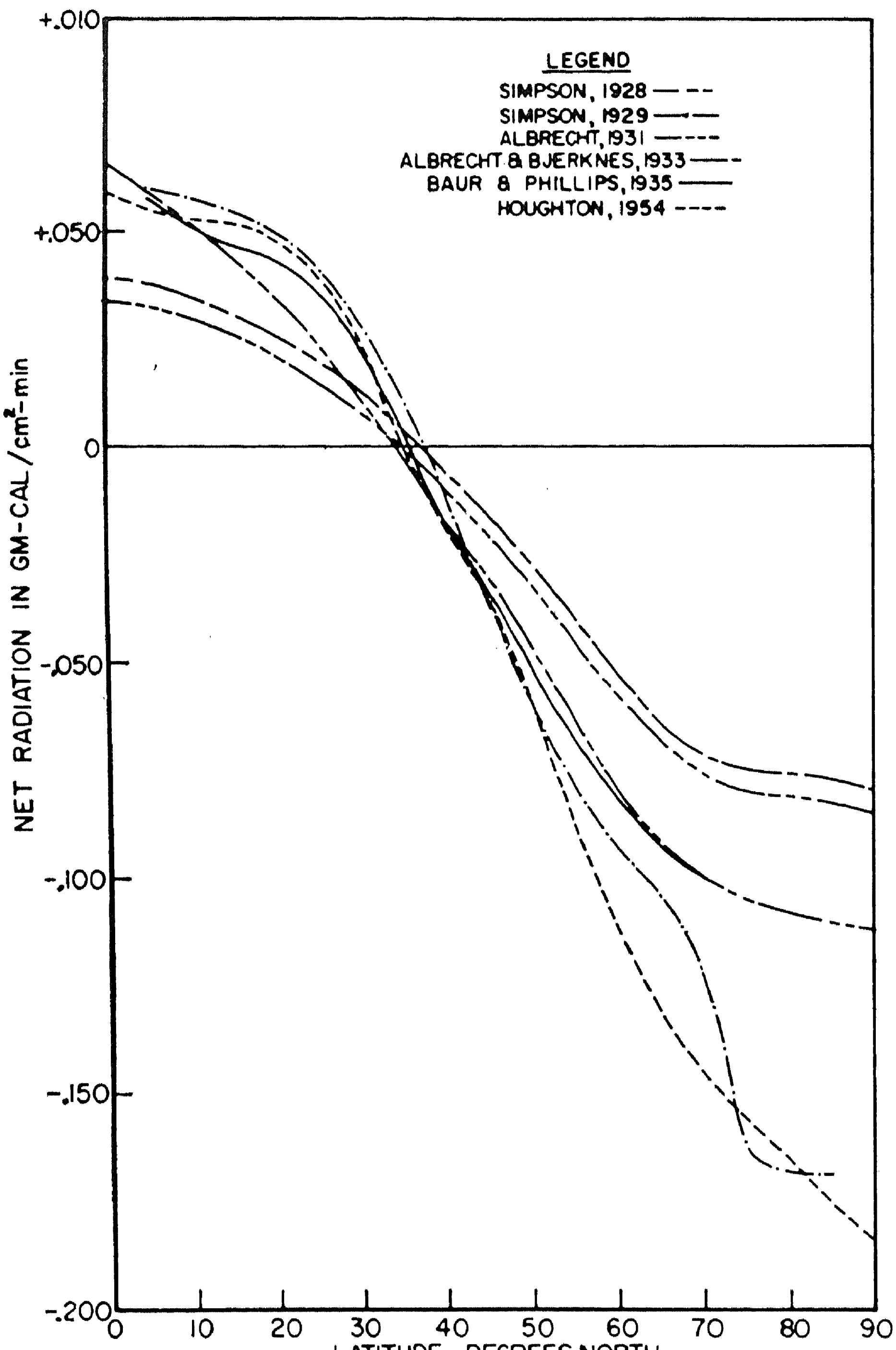

FIG. 1 — Amount of net radiation for different latitudes; annual average values for northern hemisphere [*Jung,* 1956]

year. Now we all agree that the distribution of the net radiation ultimately drives the atmospheric circulation. Significant short-term changes in radiation may occur which in turn may influence the subsequent circulation of the atmosphere. If so, satellite observations would give us important information about the changes in world-wide radiation, information which cannot be obtained now in any other way.

The satellite observations can give us the sum of the solar energies absorbed in the atmosphere and by the Earth's surface. To find the energy absorbed directly in the atmosphere, we need, in addition, observations of the energy reaching the ground. Ground-radiation measurements are not plentiful; but in the United States, we do have a fairly good network of solar radiation observations. If the satellite passes over the United States during midday, we should get a good estimate of the solar energy absorbed in

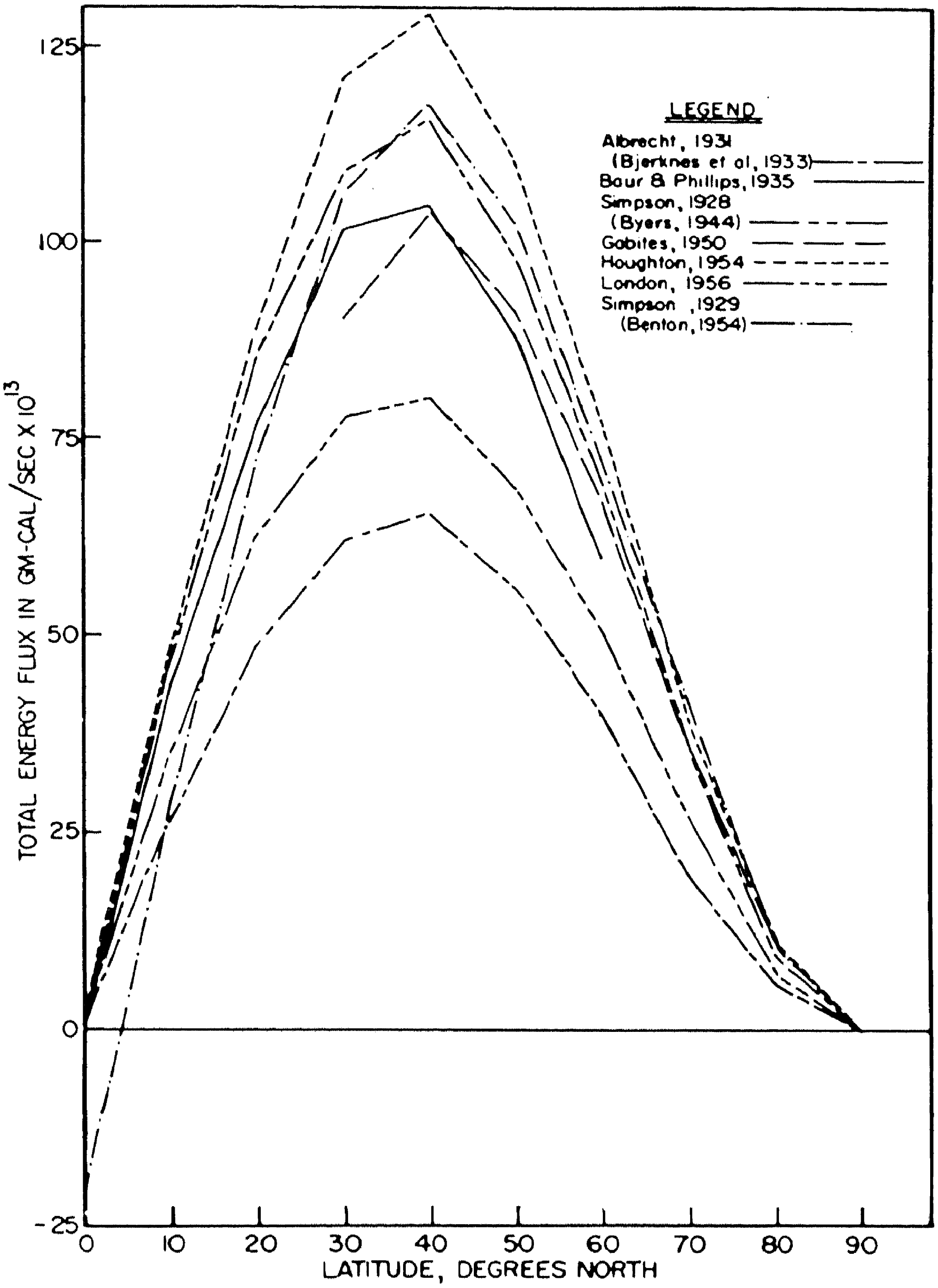

FIG. 2 — Total energy flux across complete latitude circles required to balance net radiation; annual average values for northern hemisphere [*Jung*, 1956]

the atmosphere from a combination of the satellite and ground measurements.

Another satellite experiment, planned by the Army Signal Corps, is the measurement of the cloud-cover distribution over the Earth. Photocells, mounted in the satellite, will scan the Earth below and record the changing brightness of the reflected solar energy. Bright areas will in general correspond to cloudy areas, dark areas will correspond to cloudless areas.

Lunar observations; albedo of the Earth—The variations of the Earth's albedo or reflectivity will also be measured by observing the brightness of the light and dark sides of the Moon. This program will be carried out by personnel of the Smithsonian Institution at various satellite optical tracking installations. The dark portion of the Moon is irradiated with sunlight which has been reflected to it by the Earth. Thus, the dark side of the Moon will be brighter, the brighter the Earth is. Measurements comparing the brightness of the dark and bright sides of the

Moon have been made by *Danjon* [1936] and by *Dubois* [1955]. Large seasonal variations and large variations with sunspot cycle have been reported by them. In Dubois' measurements the variations of the albedo of the Earth were especially large, varying by about a factor of 3 from sunspot maximum to sunspot minimum. During IGY at least the seasonal variations will be checked. But what will be equally important for this type of measurement will be the comparison of measurements made by two observers along the same longitude but in opposite hemispheres and therefore in opposite seasons. These observers will be viewing the Moon which will be illuminated by essentially the same region of the Earth. If their measurements of albedo agree consistently, this will provide a valuable check of the method.

Good observations of the Moon will provide us with basic data regarding the Earth's albedo and its time variations; this in turn will supplement the satellite data and eventually may help in our understanding some of the basic characteristics of our atmospheric circulation.

Heat budgets of polar regions—Heat budget studies of selected regions of the Earth's surface will also be made during IGY. Some of these will be conducted in the Arctic and Antarctic regions. Since the main objective of IGY is to learn as much as possible about the Earth, such studies will serve this objective by supplying additional basic data for regions about which we know very little.

As a guide to the type of information needed, Figure 3 contains an analysis of solar radiation data obtained on T-3 (Fletcher's Ice Island) in 1953. In mid-June the average radiation received in one day was about 700 ly/day (1 langley = 1 cal/cm^2), while in Washington, D. C., the average is only about 500 ly/day. The higher measured value in the polar regions is caused by the longer day and by the multiple reflections between the snow-ice surface and the over-lying clouds and atmosphere. Good observations of solar radiation received on a horizontal surface at the ground were obtained at T-3, but in order to calculate how the solar energy is used to modify the ice and atmosphere we needed much more information. Much of the solar energy is reflected by the ice and snow, but we had no good measurements of albedo. Both T-3 and ice-floe Station A have now been occupied and an albedo survey of T-3, and of the ice-floe Station A is planned. From a good estimate of albedo we then will know how much energy is absorbed by the ice.

In mid-summer, the ice may or may not also lose energy through long-wave terrestrial radiation. Here again, we expect to have good measurements of the net radiation and of the down-coming energy from the Sun and atmosphere. During overcast conditions, the long-wave energy lost from the ice should be very small; there may even be a gain by the ice. And in the Arctic the sky is nearly always overcast in midsummer. Therefore, for lack of actual good data in the

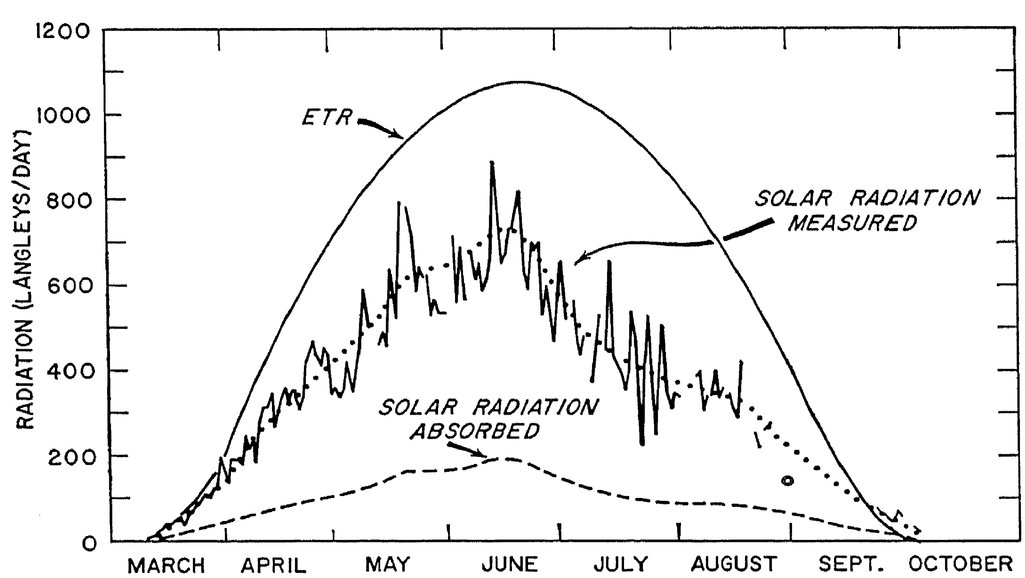

FIG. 3—Solar radiation on T-3, in 1953; curve marked ETR (extra-terrestrial radiation) is solar energy received on a horizontal surface outside the Earth's atmosphere at the latitudes of T-3

1953 analysis, we assumed that the long-wave energy loss was zero, although this cannot be strictly correct. But during IGY observations will replace this assumption.

The net radiation is the difference between all the radiation fluxes which reach the ice and those which leave it. This net radiation is available for melting ice, or raising its temperature. Some of the measurements of ice temperature were made in 1953 but more and better ones should be available soon. The amount of energy which goes into melting is difficult to estimate because of the irregularity of the ice surface, causing lakes to form in some areas, while water runs off in others. Nevertheless, from ablation stakes and estimates of the volume of water in the lakes, it may be possible to get a good estimate of the energy used up in melting.

After estimates were made for these various factors, it was still not possible to balance all the radiation terms; a net surplus of solar energy still remained. Transport of heat by horizontal advection could not account for this, because of the very uniform surface temperatures over the melting Arctic ice. Vertical energy transfer seemed like a reasonable method for disposing of the energy. And this seemed even more reasonable after we looked at the radiosonde data. For in the lowest 300 to 1000 ft, the fall of temperature with height exceeded the adiabatic lapse rate frequently during July 1953. This strongly suggests that both sensible heat and latent heat were transferred upward by eddies from the ice surface to the ever-present cloud surface. The heat would then be lost from the cloud top by radiation and evaporation.

These super-adiabatic lapse rates have been questioned. It is difficult to get precise radiosonde information about these super-adiabatic lapse rates in such shallow layers because radiosondes ascend rapidly. Therefore, captive kitoons will be used in the Arctic to supplement the radiosonde data in the lower layers.

Thus measurements of net radiation, solar radiation, ablation, ice temperatures, and of temperatures and moisture structure in the lowest layers of the atmosphere, will furnish data both to the glaciologists about the ice regime, and also to the meteorologists about the temperature structure of the lower atmosphere.

Similar radiation programs are being carried out at six stations in Antarctica. On the basis of previous work, a study is now going on to find the lowest possible temperature at the South Pole Station where the temperature has already fallen below −100°F. The IGY measurements will be useful in extending such studies.

Furthermore, the radiation data collected in the Antarctic and Arctic regions will supply data for many endeavors. Human comfort certainly depends on radiation. Two examples: (1) The design of clothing depends on radiative energy loss and gain. (2) The usefulness of solar batteries for energy supply depends upon the amount of available solar energy.

The polar whiteout—Aside from its usefulness in energy studies, radiation measurements are also needed to investigate certain physical problems. The polar whiteout has long been recognized as a hazard to aviators. *Fiske* [1956] has recently re-emphasized this. The whiteout occurs when the ground is completely covered with fresh, cold snow. Then when the sky is overcast so that the position of the Sun is not discernible, no shadows are cast. Natural terrain features such as hills or mountains cannot be distinguished against the horizon sky. Nor can crevasses or small surface irregularities be seen against the snow background. These conditions create a hazard for both surface and air travel. *Fiske* [1956] points out that helicopter operation is particularly hazardous during the whiteout because these planes lack proper radar instrumentation at present. Another hazard occurs even in conventional planes when a pilot descends through a low overcast and is suddenly presented with a lack of perception contrast rather than a view of familiar landmarks.

During overcast sky conditions, the zenith sky is about three times brighter than the horizon sky when the ground is not snow covered; but until recently no measurements were available above a snow covered surface. To test the theory further, measurements of sky brightness distribution will be made during overcast conditions at Little America and at T-3. At the same time the albedo of the snow surface will be measured in visible light. It will be interesting to see how the overcast sky-brightness distribution will vary with and without whiteout conditions, and if the limit is related to the surface snow albedo as theory suggests. If so, we may be able to predict the severity of the whiteout by fore-

casting the surface albedo which in turn depends on temperature and other factors.

Atmospheric Composition

Total ozone—Ozone is a gas which is distributed vertically in the atmosphere with a maximum near an altitude of 20 to 30 km. The amount of ozone in any vertical column varies with changes in atmospheric circulation. Therefore ozone measurements may give us some important clues about the horizontal and vertical motions in the lower stratosphere. Ozone will be measured in North America at 13 stations as shown in Figure 4. (By April 1958, several changes have occurred. Many of the proposed stations are in operation. The instrument at Fairbanks, Alaska, has been moved to State College, Pennsylvania.) With this network we have an opportunity to study the ozone changes associated with the long-wave patterns of atmospheric motion and particularly to seek relationships between the stratospheric and tropospheric weather elements.

Total atmospheric ozone is measured with the Dobson ozone spectrophotometer which analyzes the ultraviolet light which has arrived from the Sun. Ozone absorbs certain ultraviolet light strongly, the amount of light which arrives in the ozone absorption band is compared with the light outside the band. If much ozone exists above the observer, the amount which arrives through the ozone band is small; with little ozone overhead, the amount of ultraviolet light is large.

Ozone measurements in the Antarctic are completely lacking; therefore ozone cannot help us in theoretical studies about large-scale motions in the stratosphere over the polar regions of the southern hemisphere. An attempt to fill the void in ozone data is being made with the Dobson ozone spectrophotometer which W. B.

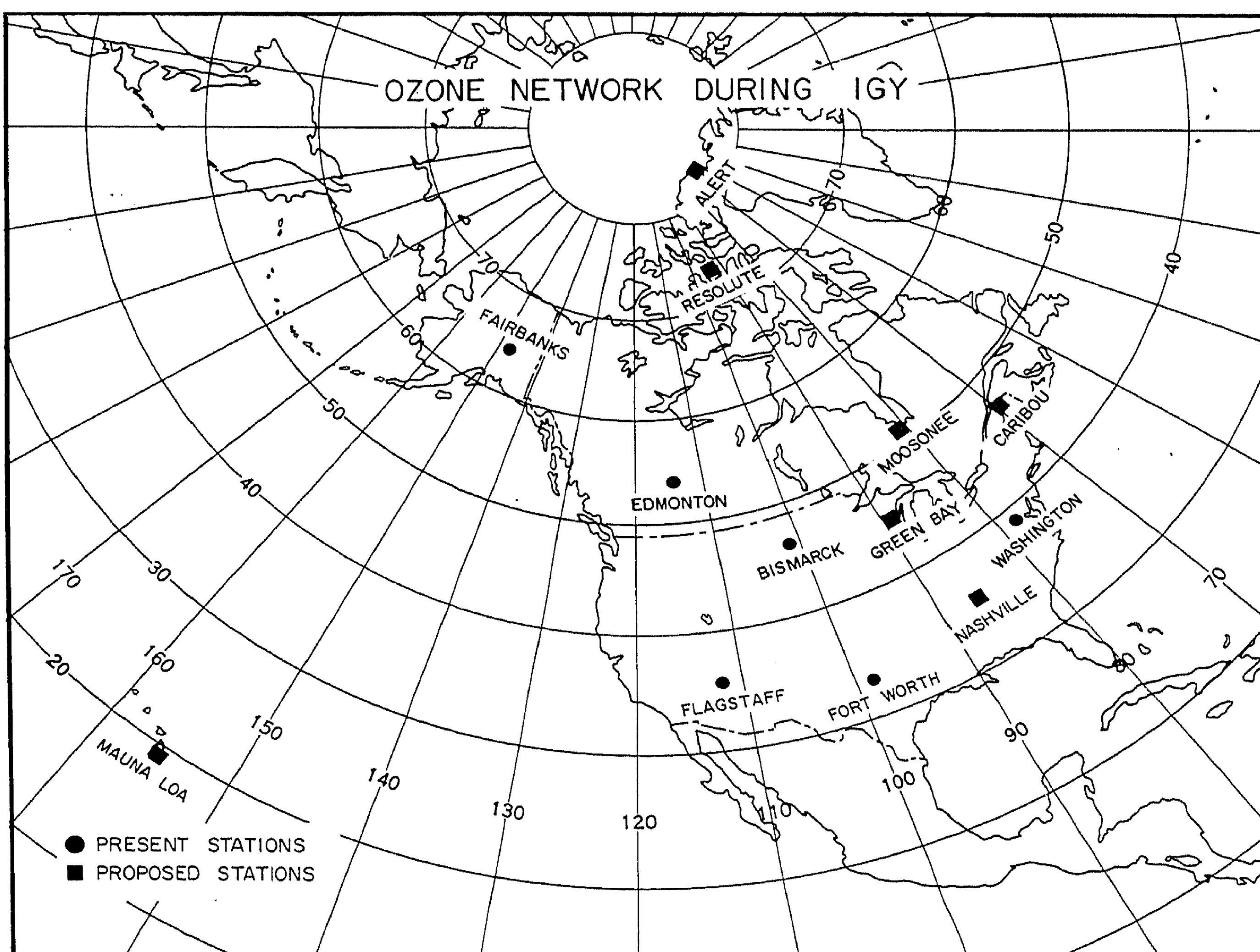

Fig. 4—The network of total ozone measuring stations during IGY in North America and Hawaii

Moreland is operating at Little America. (April 1958: Moreland has now returned from Little America where he made some lunar ozone measurements.) Unfortunately, it is quite difficult to obtain good measurements at night with this instrument, but lunar measurements will be attempted. To do this we need to measure as the Moon undergoes a large variation in angular elevation. This cannot be done in Little America; but we are establishing a station at the Mauna Loa Observatory at 11,300 ft above the Pacific Ocean, where we hope to get the required measurements as the Moon's elevation varies during the night. (April 1958: This station is now in operation.) Thus the equatorial and polar regions will be supplementing each other.

Ozone is also responsible for the large annual variation in temperature in the polar stratosphere. Measurements of the amount of ozone may help in further understanding the pronounced summertime warming which causes the winter west wind to become summer easterlies in the stratosphere above 20 km. Ozone measurements have already been useful and will be of further aid in studying the very pronounced temperature increases which occur some years near 25 km at high latitudes in winter.

Surface ozone—Surface ozone will also be measured near both poles, and at Mauna Loa. Ozone near the Earth's surface gets there by downward diffusion from the ozone-generating region above 20 km. Since ozone is destroyed near the ground, this means that a continual downward diffusion is occurring and surface-ozone measurement may shed some light on the magnitude of this downward diffusion, although the vertical ozone gradients will probably be required to pin this down better.

Carbon dioxide—The air temperature near the ground would be much colder than it is now if certain atmosphere constituents such as CO_2 and water vapor were not present to produce the so-called greenhouse effect in the atmosphere by absorbing outgoing energy and radiating it back to the surface. With regard to CO_2, at least two questions arise. These are: (1) Would the surface air temperature increase if the amount of CO_2 in the atmosphere were to increase? (2) Has the amount of CO_2 increased in recent times, and if so, what is its present trend? It is true that man is pouring vast amounts of CO_2 into the atmosphere. But because the oceans, rocks, and plant life tend to produce an equilibrium with CO_2, it is not at all certain that CO_2 is increasing in the atmosphere; the added CO_2 may have gone into the oceanic or biological realm.

To investigate this we need to know at least the present amount of CO_2 in the atmosphere. CO_2 is being measured in the Antarctic and many flasks will be filled with air in many regions of the world. Measurements will also be made from U. S. Air Force Weather reconnaissance aircraft and from surface observations.

With these data, some comparisons will be possible with past data. But because the past data have been made with various good and bad techniques in pure and in contaminated regions, comparison will have some, though limited, usefulness. The data will be particularly valuable as a basis for comparison during future surveys and future IGY's. One of the leading theories about the recent observed warming in the Arctic Ocean and in some other portions of the world, attributes this warming to an increase of artificial CO_2 in the atmosphere. The IGY measurements will be an important link in proving or disproving this theory.

The program for measuring nuclear radiation—The advent of the nuclear age and the consequent injection of large amounts of nuclear debris into the atmosphere has yielded another tool which may, together with studies of naturally occurring radio-elements, provide useful geophysical information. The radioactive content of the atmosphere can possibly serve as a useful tracer for studying movements of air masses and large-scale circulation patterns. This tracer may also be used to study removal processes in the atmosphere. Natural radioactive elements, such as tritium, $carbon^{14}$, and radon decay products can be used to study mixing processes and stratospheric-tropospheric exchange phenomena in the atmosphere. Artificial radioactive elements can be used to supplement this. Radioactive isotopes are also useful in oceanographic investigations in problems of circulation, mixing and age determination.

The United States, in cooperation with other western hemisphere countries, is establishing a network of surface radioactivity monitoring stations along the 80° W meridian. Well over ten stations will soon measure the air concentration of long-lived fission products in the lower atmos-

phere with high-volume air filters and from the amount deposited in precipitation. This network will stretch from the Antarctic to the Arctic. In addition, a network of about forty stations in the United States is making daily measurements of the air concentration of the long-lived fission products and a world-wide network of 88 stations makes daily collections of deposited radioactivity on gummed film. Several stations in each hemisphere are planned to collect precipitation and total fallout in open tubs. In addition, there are four stations measuring the radioactivity in the upper atmosphere to heights of about 100,000 ft by means of balloon-borne collectors. Various oceanographic programs will collect sea water for analysis of radioactivity.

These networks are all designed to measure long-lived artificial radio-nuclides, but in addition, some stations are going to measure short-lived natural radioactivity in the atmosphere. It is hoped that these programs will shed new light on circulation and mixing processes in the atmosphere and the oceans and on removal mechanisms in the atmosphere.

Acknowledgment—The information about the radioactivity measuring program has been supplied by L. Machta and R. J. List of the U. S. Weather Bureau, Washington, D. C.

References

Danjon, A., Nouvelles recherches sur la photomètrie de la lumière cendrée a l'albedo de la terre, *An. Observatoire Strasburg*, 3, 139–180, 1936.

Dubois, J., La variation de brilliance de la lumière cendrée de la lune, *L'Astronomie*, 69, 242–246, 1955.

Fiske, C. O., White-out, a polar weather phenomenon, *U. S. Naval Inst. Proc.*, 82, 955–959, Sep. 1956.

Jung, G. H., Energy transport by air and sea, OPNAV, Po 3–8, Contract N 7 ONR-48702, Tech. Assistant, Chief Naval Op. for Polar Projects, *The dynamic North*, Book 1, chap. 14, 19 pp., 1956.

U. S. Weather Bureau, Washington 25, D. C.

Synoptic Studies in Oceanography

Columbus O'D. Iselin

Introduction—A central and classical problem in physical oceanography is to try to understand the circulation of the oceans as a whole. In order to do this it is, of course, first necessary to be able to describe the three-dimensional distribution of the physical and chemical properties of the whole fluid envelope. Until now it has only been practical to secure satisfactory data from rather limited areas. Only a small per cent of the observations have been from depths greater than 3000 m, although most of the ocean is nearly twice this deep.

Oceanographers have had to be content to study a sort of average ocean constructed from the observations of temperature and salinity and dissolved oxygen obtained by many ships. The distribution of such data is very uneven, both in time and in space. The accuracy of even the best of the observations has only been satisfactory during the past 30 years or so. Only one ocean, namely the South Atlantic, has ever been surveyed systematically and in a manner that could essentially be regarded as providing a synoptic picture of the deeper water masses. Nevertheless, it has become possible to describe the physical and chemical structure of the oceans in broad outline, and in recent years through multiple-ship operations a beginning has been made in synoptic oceanography in limited areas.

There is every expectation that through the International Geophysical Year the basic data of physical oceanography will be improved by a whole order of magnitude. If present plans can be carried out, this will be especially the case for the deeper water masses.

It must be admitted that oceanographers at the working level in this country were at first not too enthusiastic about the prospects of adding significantly to our understanding of oceanic circulation during the International Geophysical Year. It was argued that our ships were already working on a year-round basis and that the existing programs of research at our laboratories were the best that could be devised. When the desirability of periodic resurveys of the whole system of currents was pointed out, few oceanographers at the working level had the patience to wait for another 30 years or so to pass before it might be practical to learn more about the gradual changes that might be taking place. Some of us also felt that we were being asked to plan a survey of the oceans that our sons would want to repeat and, because of the very rapid advances in our concepts of the basic problems during recent years, there was doubt that any program that could now be organized would in retrospect seem wise.

During the planning period three factors, at least, have helped to stimulate greatly enthusiasm for the IGY oceanographic program. In the first place, nobody foresaw how many research vessels would be able to cooperate. As soon as it became evident that as many as 60 ships might become available, many people's attitudes, including my own, changed rather abruptly. For some reason international cooperation in oceanography has been slow to develop, although of course it has been obvious all along that no one nation is likely to bring to bear sufficient resources to do a thorough job of studying more than a limited part of the world's oceans. However, with so many ships available it would indeed be possible to gain a rather complete look at the deeper waters on a more or less synoptic basis. The fact that all the data would be secured within a two-year period would be quite satisfactory in this case, for the deeper currents are believed to be sufficiently slow so that not much change is likely to occur in the system during such a period of time.

A second encouraging factor stems from the recent observations of L. V. Worthington of the Woods Hole Oceanographic Institution. He has shown that below a depth of about 2500 m in the western half of the North Atlantic the waters today contain about 0.3 cc less dissolved oxygen per liter than was the case 25 or 30 years ago. This is strong evidence that the deeper water has not been renewed during this period. Thus an easily measurable change has taken place in the North Atlantic and it will be interesting to learn whether or not slow trends are also taking place in other areas. In the case of the South Atlantic a particularly complete

survey of temperature, salinity, and dissolved oxygen was made by the German ship *Meteor* during the period 1925–27. Thus to repeat some of these observations became one of the major objectives of the United States oceanographic program for IGY.

A third factor to arouse interest in deep currents has been the recent success of J. C. Swallow of the National Institute of Oceanography in England in obtaining direct measurements of the flow at considerable depths. In the past the interpretation of deep measurements of temperature and salinity in terms of direction and velocity has been beset by very considerable uncertainties. The question at issue can be stated in deceptively simple terms: How deep are the more powerful, permanent ocean currents? If they are relatively shallow, that is to say extend down to only 1500 m or so, then below them the distribution of density and the available theory demand that deep countercurrents exist. Many different kinds of studies have been made in an effort to resolve this problem during recent years, but until Swallow developed neutrally buoyant floats, there was rather little hope of gaining a clear-cut answer.

The influence of these three developments on the U. S. Atlantic IGY oceanographic program has been very marked and, in fact, a good deal of the work has already been completed, so enthusiastic have people become. Similar efforts in the Pacific lack the stimulus of as complete a set of early measurements for comparison with the deep physical and chemical situations as they exist today, but it seems safe to say that the successes to date in the Atlantic are likely to encourage corresponding efforts in other areas.

As mentioned above, the Atlantic oceanographic program has already achieved some preliminary results. In trying to predict what the whole very considerable undertaking will amount to, it will be helpful to discuss these first observations.

Pre-IGY Program

Observation of currents—The program really began in March 1957 when the British research vessel *Discovery II* and our *Atlantis* met at Bermuda. During the next six weeks their joint operations were so productive that it is clear that a real milestone in physical oceanography was achieved. The area selected for the work was the outer edge of the Blake Plateau at about the latitude of Charleston. It was known from previous *Atlantis* temperature and salinity sections that in this area the deep water flow (whatever its direction) was forced well east of the swift and much shallower Florida Current by the Blake Plateau. Thus in this area the ships would not be handicapped by strong surface currents in their efforts to relate the deep water movements to the deep density structure. Farther north the deep density gradients are just as pronounced, but they lie more directly under the Gulf Stream. Because of the availability of Loran navigation in this area, both ships could have excellent navigational control.

While the *Atlantis* measured the deep temperature and salinity structure at stations often as close as two miles apart, the *Discovery* tracked neutrally buoyant floats drifting with the water at preselected levels. The floats contained a sound source and the tracking was achieved through two hydrophones suspended from the bow and stern of the *Discovery*.

With the float at 2000 m the net motion at the end of four days was so close to the resolving power of the technique that the total drift of only a few miles was not significant. Shallower floats clearly drifted to the northeast, as was expected, and with the expected velocities. But a float set out at 2800 m went toward the southwest at about eight miles per day. Thus, in this part of the North Atlantic, the level of minimum motion is at about 2000 m and below this the current is moving surprisingly rapidly in the opposite direction.

Many more such observations are, of course, needed before it can be known with certainty how widespread this unexpected phenomenon may be, but at least two things were made very clear through the work accomplished to date: Through international cooperation results were achieved by pooling ships and observers that neither group could have accomplished alone and, furthermore, it should be possible through similar operations in a few other carefully selected areas to interpret with considerable assurance the great mass of deep temperature and salinity observations that will be secured by the other IGY ships. Just a few weeks' work by two ships has made the whole deep-water program much more meaningful. Until this operation, the main hope that scientific sense

would be achieved was that somehow the chemical observations made during IGY could be brought into agreement with the movements of the water deduced from the distribution of density. There is always more or less uncertainty in this general approach to the deep circulation problem for lack of quantitative information of the role of biological activity in altering the distribution of the usually observed chemical constituents of sea water.

Chemical measurements—On her way back to Plymouth from the operations off Charleston, with some help from scientists at Woods Hole, the *Discovery* achieved the most complete North Atlantic profile to date. Temperature, salinity, and oxygen were measured at 40 stations on a line from the Grand Banks of Newfoundland to the approaches to the English Channel. This work sets a very high standard for completeness and accuracy which the other European ships crossing this area during the next 18 months may be hard pressed to match. The accuracy of the salinity determinations was especially high due to the use of a new sea-going conductivity bridge developed recently at Woods Hole.

Meanwhile, the research vessel *Crawford* from Woods Hole, under the skillful leadership of F. C. Fuglister, had made four complete Atlantic crossings; two in the tropical North Atlantic and two in the tropical South Atlantic. The two latter sections are duplicates of two of the *Meteor* crossings of 30 years ago. In short, we have already realized five complete Atlantic east-west profiles and three more are scheduled for the same ships before the end of the next year.

The reasons for 'jumping the gun' with the *Crawford* are the same that prompted Maurice Ewing of the Lamont Geological Observatory to send the *Vema* into the South Atlantic in the winter of 1957. Next winter the *Atlantis* and the *Vema* are scheduled to operate together in the South Atlantic during a six-month period. It was felt that we could make much more effective use of this time if we had the benefit of some reconnaissance. Furthermore, the Russian and the Argentine ships that will cruise in the South Atlantic during the next year or more could also benefit. When the winter's work of the *Crawford* and the *Vema* has been studied in a preliminary manner, we should all be in a much better position to plan wisely for the main assault.

Since the *Crawford* only returned to Woods Hole on June 1, 1957 after a four-month voyage, I can give here only one example of her work. This is a profile of temperature (Fig. 1), salinity (Fig. 2), and oxygen (Fig. 3) following latitude 15°45′ S. This is a reoccupation of one of the *Meteor* sections. The sampling intervals both vertically and horizontally are indicated by dots on the oxygen profile. In comparison with the *Meteor* profile about twice the number of observations were secured.

So far as temperature is concerned, there are no striking changes. The deep temperature gradients near the South American continental slope are steeper than in the *Meteor* profile, but in all probability this is just a consequence of the closer station spacing. The temperature maximum at mid-depths in the west has increased by about 0.3°C. The salinity profile, too, corresponds very closely to the one secured by the *Meteor*. There is more detail in the slight salinity fluctuations at mid-depths, due both to the greater accuracy of the new observations and to the more closely-spaced points of observation, but at first look there seems to be no large-scale difference.

On the other hand, there have been quite pronounced changes in the dissolved oxygen values during the 30-year interval. This is most easily seen by comparing the individual oxygen-depth curves shown in Figure 4. Especially near the two ends of the profile there is more oxygen today in the oxygen minimum layer and less in the deeper waters. The Antarctic bottom water at depths below about 4000 m in the western basin has lost as much oxygen as the deep water in the western basin of the North Atlantic. Presumably of recent years the deeper water is not being renewed because sufficiently dense surface water is not formed in winter, either in the far north or the far south. It is interesting to speculate about how long the trend will continue.

The three other 1957 *Crawford* profiles are of just as high quality and I think that all oceanographers will agree that this is a remarkable piece of work for so small a vessel; the *Crawford* when fully loaded displaces barely 300 tons. The data shown here are just one part of a very much broader program of observations.

Those who are familiar with the recent papers of George Wüst of Kiel University know the immense amount of work that he has devoted over a long period of years to the interpretation

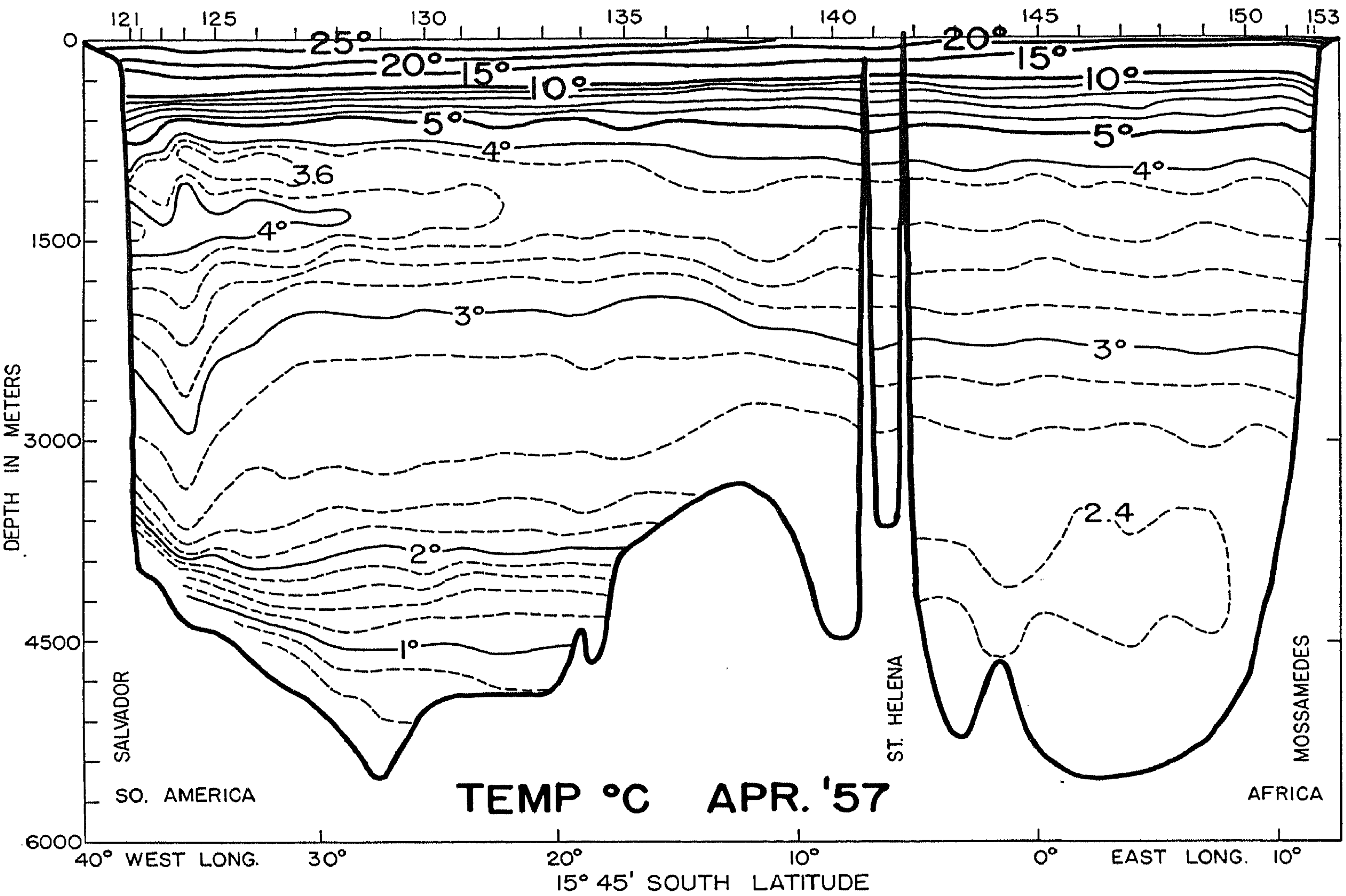

FIG. 1 — Temperature profile taken by the *Crawford,* 1957

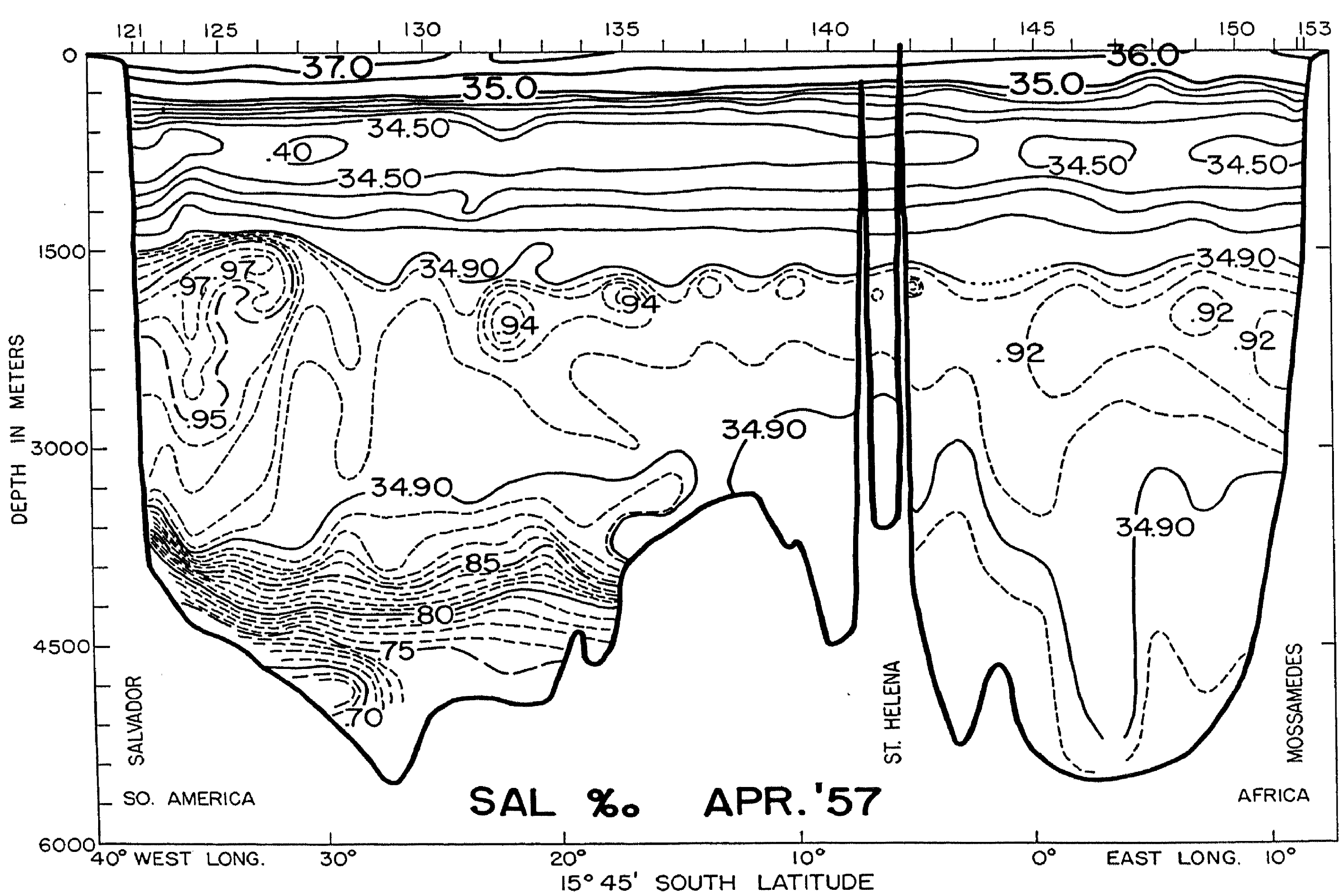

FIG. 2 — Salinity profile taken by the *Crawford,* 1957

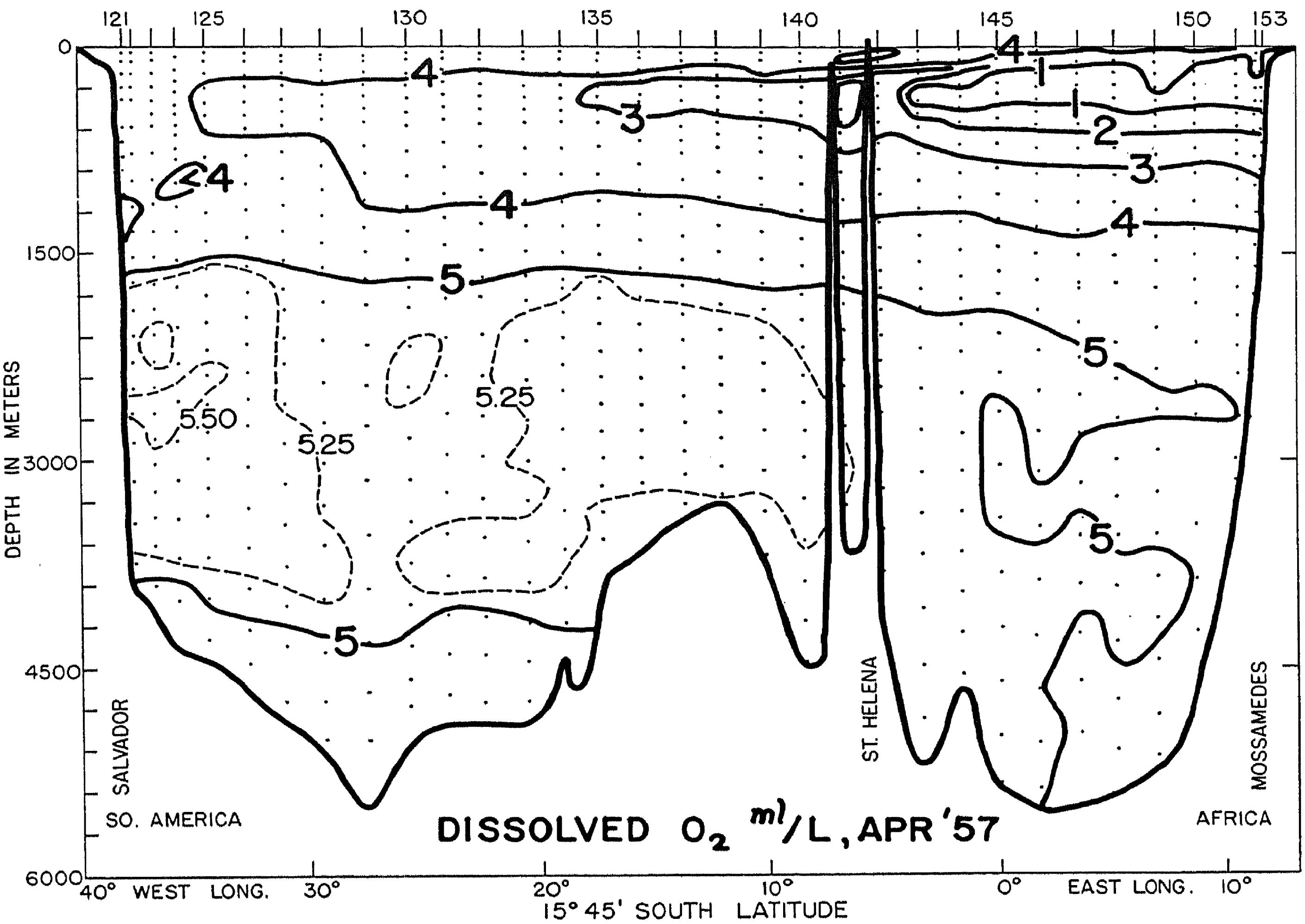

FIG. 3 — Oxygen profile taken by the *Crawford,* 1957

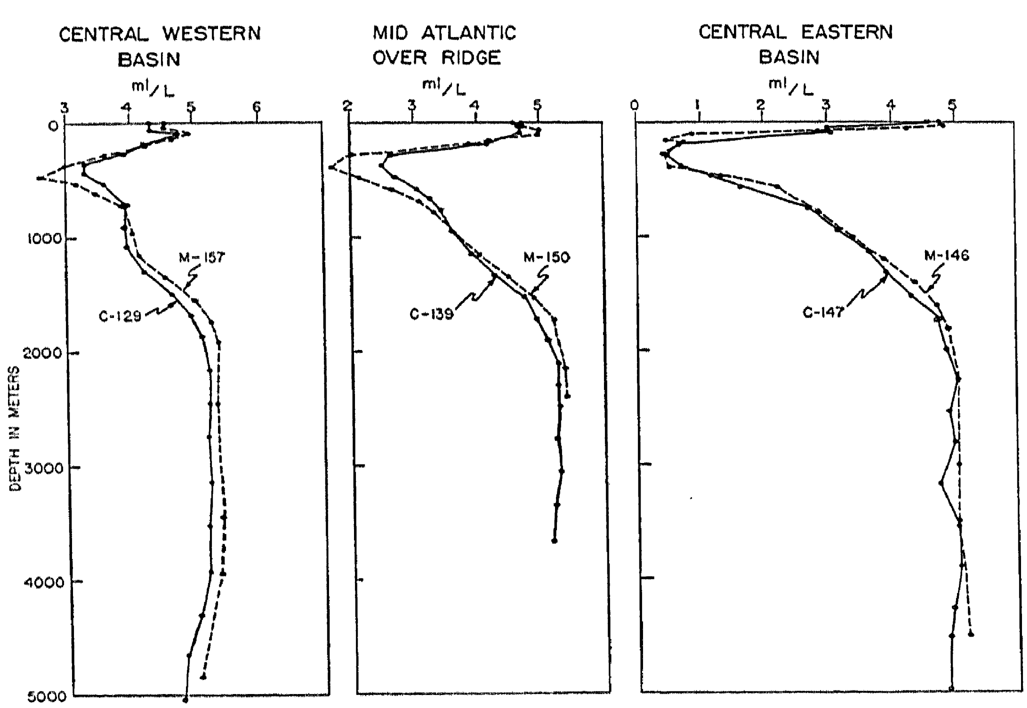

FIG. 4 — Dissolved oxygen observations at selected stations, 15° 45′ S latitude

of the *Meteor* profiles in terms of transport and velocity. He has worked out some fairly convincing arguments that there are three levels of minimum motion in the South Atlantic. The cold and relatively fresh Antarctic bottom water has a northward component, the great mass of water at mid-depths having salinities just above 34.90‰ (parts per thousand) has a southward component. The salinity minimum layer with its axis at about 700 m is moving north, while nearer the surface there is a southward component. Although most oceanographers will agree that the net components of motion are in these directions at the various levels, the rates of flow computed by Wüst seem to some of us to rest on much shakier ground. Thus, it will be of great interest to set out next winter some of the Swallow-type, neutrally buoyant floats at the critical points in these South Atlantic profiles. Study of the new *Crawford* profiles will help in the selection of the best depths and locations for gaining this very positive type of observation.

Conclusion

To gain reliable information about the surprisingly swift and narrow deep flow in both the North Atlantic and the South Atlantic, which are the most thoroughly explored and best understood oceans, will not only be of interest in itself, but will also help greatly in the interpretation of the deep observations that will be made by ships operating in the South Pacific and Indian Oceans, which are nearly virgin territory so far as three-dimensional oceanography is concerned.

The rate of overturn of the oceans as a whole is not just an oceanographic problem that is basic to many lines of inquiry in biological and geological oceanography, as well as in physical and chemical studies. Since the ocean acts to some degree as the fly-wheel in the great heat engine in which the motions of both the atmosphere and the hydrosphere combine and interact on each other, such studies are also basic to a better understanding of climatic trends, to the possible use of the deep ocean for the disposal of radioactive waste materials, and to other more or less practical matters. In the past the problem has been attacked by many individual investigators and by a few research vessels working independently. This will be the first time that a large percentage of the world's talent and facilities for oceanography will be working within an agreed cooperative program.

If the quality of the data secured during the winter of 1957 by the *Atlantis,* the *Crawford,* and the *Discovery* can be matched by most of the other research vessels taking part in the International Geophysical Year programs, there is little doubt that a considerable stride forward in our understanding of the oceans will soon be achieved.

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

The Seasonal Budget of Water

Walter H. Munk

Suppose one were to examine the Baltimore tide record after suppressing daily and semi-daily tides by a suitable scheme of averaging. The record would then show a pronounced seasonal trend. The mean level in March would be lower by something like 20 cm than in September. This result is not an isolated instance, but part of a coherent picture in the entire North Atlantic Ocean. A relatively low sea level in February to May by a sizable fraction of a foot can be found along the East Coast from Florida to Maine, at Bermuda and the Azores, from the Mediterranean to Norway, along Greenland and Iceland [*Pattullo* and others, 1955]. In general terms this holds also for the North Pacific Ocean. In the southern hemisphere the relation appears to be reversed, with sea level high in March and low in September. "Sea level is low in spring" may serve as a very rough first approximation.

What are the causes of this seasonal variation in sea level? It is far easier to say what cannot be the principal causes. The gravitational attraction of Sun and Moon give rise to a seasonal tide about ten per cent of the observed value. The yielding of the sea surface under the direct effect of atmospheric pressure likewise amounts to only about one-tenth the observed amount. Apparently the largest effect, at least in moderate latitudes, is the heating and cooling of the water by solar radiation, back radiation, evaporation, etc. [*Pattullo*, 1957].

In turn this means that most of the observed variation in sea level represents a thermal expansion and contraction of the water rather than a shifting water mass. A pressure recorder at the sea bottom would note a relatively small seasonal variation, that is, conditions are nearly 'isostatic.'

In high latitudes the situation is apparently different. From what one can tell on the basis of the present very inadequate data, conditions there are not at all isostatic. It looks as if during winter in each hemisphere, water is moved from the polar and subpolar seas into the subtropical regions; in summer the transport is in the opposite sense. (The fact that the Arctic Ocean partakes in this seasonal trend is known to us due to the cooperation of Russian oceanographers who made available some observations in response to a request at the Brussels IGY meeting, 1955. Previously no Arctic tide observations of sufficient duration had been known to us.)

Our present picture is based on something like 500 tide gage stations. During IGY we expect to occupy an additional 200 to 250 stations. The positioning of these stations has been determined largely by the gaps in the present distribution. Accordingly the emphasis is, in the order given, on (1) islands, (2) the southern hemisphere, and (3) measurements of the specific volume of water so that the degree of isostasy can be computed.

The international scale of this undertaking is noteworthy. At the time of this writing, the United States and Argentina have plans for 20 stations each, New Zealand, South Africa, and Spain plans for 15 stations each, Mexico 14, Australia 11, Italy and USSR 10 each, etc. The present total is 226 stations to be established by 27 countries. One of the American stations will be located at Pt. Barrow, Alaska, with special efforts to obtain records even when the sea is frozen.

So far we have dealt with shifts in water mass within the oceans. On the basis of the present data we have attempted also to find out whether the total mass of ocean water varies appreciably throughout the year. Our best guess is that between October and March the northern hemisphere oceans lose 2×10^{19} grams, while southern hemisphere oceans gain 1×10^{19} grams, leaving a net loss of 1×10^{19} grams, equivalent roughly to a sea level drop by 4 cm [*Munk*, 1956]. The uncertainty is such that the total loss may be twice as large or there might be none at all. We do hope that the IGY effort will narrow the uncertainty by a good deal.

Suppose we accept the above values for the moment. Where can one store 10^{19} grams of water during March? The atmosphere contains two to three grams of water per square centimeter, and the seasonal variation is only about ten per cent of this value. This is inadequate.

Snow over Siberia alone amounts to about one-third of the required amount, and maximum storage does occur at the required time, in northern spring. Recently, *van Hylckama* [1956] has completed a global survey of variable detention of moisture in the form of snow, organic material, moisture in the soil and ground water. His estimates are that maximum detention for the Earth is during March and April, minimum detention in September and October, and that the total range equals 0.5 to 0.75×10^{19} grams. In magnitude as well as phase this agrees with our rough estimates based on oceanic measurements. Thus there is some hope that the global water budget might be balanced in a rough way on the basis of the IGY effort.

There is, moreover, opportunity for making a rough check as to whether such a budget is in accord with other considerations. Clearly a shift of water mass towards the equator increases the Earth's moment of inertia, and accordingly, if angular momentum is to be conserved, the Earth's angular velocity must decrease or the length of day increase. The expected seasonal range in the length of day due to shifts in water mass is of the order of 0.1 milliseconds. Astronomic measurements indicate a total range of about 0.7 milliseconds. Most of this range is due to winds [*Mintz* and *Munk,* 1954] but the amount due to shifts in water is evidently not negligible. Inasmuch as the meterologic and astronomic observations will be taken with particular care during IGY, there is a possibility that the effect of shifts in water can be isolated.

There is yet another astronomic effect. On account of the asymmetrical distribution of sea and land, a shift in water mass will tilt the axis of rotation with respect to the body of the Earth. The expected amount is of the order 0″.03, or roughly a shift of the pole of rotation by three feet. The observed annual wobble is about ten times larger and caused principally by shifts in air mass. Here again there might be a chance to isolate the water term.

In closing one must emphasize that there are some difficulties associated with the water-budget problem that have not been discussed here. The reason for emphasizing this particular portion of the oceanographic program is that it fits rather well into the framework of the International Geophysical Year, for the following reasons: (1) global observations are definitely required; (2) the observations must be synchronous; (3) the period of the phenomenon is one year; (4) cooperation of various geophysical disciplines are required: oceanography, meteorology, glaciology, and hydrology; and (5) there is a relation to the IGY program involving precise determinations of longitude and latitude.

References

Mintz, Yale, and Walter Munk, The effect of winds and bodily tides on the annual variation in the length of day, *Mon. Notes R. Astron. Soc., Geophys. Sup.,* **6**, 566–578, 1954.

Munk, Walter, Geophysical Discussion, R. Astr. Soc., *Observatory,* **76**, 56–57, 1956.

Pattullo, June, The seasonal heat budget of the oceans, Dissertation, University of California, 1957.

Pattullo, June, Walter Munk, Roger R. Revelle, and Elizabeth Strong, The seasonal oscillation in sea level, *J. Marine Res.,* **14**, 88–155, 1955.

van Hylckama, T. E. A., The water balance of the Earth, *Pub. in Climatology,* Drexel Inst. Tech., Lab. Climatology, Centerton, N. J., **9**, 57–117, 1956.

Scripps Institution of Oceanography, La Jolla, California

United States Polar Ice and Snow Studies in the International Geophysical Year

Henri Bader

Introduction—It is well known that advance and recession of glaciers are usually direct evidence of a change in the local climate. If the climate does not change over a period of many years, the glacier as a whole remains stationary. This does not mean that it is not moving, but that it is in equilibirum in the sense that the amount of ice melting away in the lower parts is equal to the amount flowing down from the upper reaches. The ideal stationary glacier, then, does not change its mass or shape. Now if the climate gets warmer without appreciable change in snowfall, the lower end of the glacier will recede, because more ice melts away than flows down from above. The same thing happens if the amount of snowfall decreases without change in temperature. Under opposite conditions, increase of snowfall or decrease of temperature, the glacier will advance. The ice front could remain stationary if increase in snowfall, which would tend to make the ice front advance, were exactly compensated by an increase in temperature, which would tend to make the ice front recede. In this case, however, the surface of the glacier would become steeper, and the change of climate would manifest itself in a change of slope. The reaction of a glacier to climatic change is complicated by a number of factors related to snow and ice mechanics, which are not yet well understood. Their main effect is to be observed as a time lag between onset of the climatic change and detectable reaction of the glacier to it. Generally, the larger the glacier, and the colder the climate, the greater the lag.

Temperature glaciers—Present knowledge on this subject is meager, and one of the objectives of the IGY glaciological program is to provide more data. The present state of glaciers in many parts of the world will be recorded. This is long-range research, because much of the data obtained will only become fully useful when compared with observations to be made many years in the future. In the meantime, the IGY observations on recent and present fluctuation of glaciers will yield information on recent climatic changes and present trends in regions where meteorological records are poor. These regions of course are the higher mountains at lower latitudes and the polar regions. With very few exceptions, the mountain glaciers of the tropics and temperate regions are temperate glaciers, characterized by ice at the melting point. A relatively thin surface layer of a temperate glacier is cooled below the melting point during the winter; the large bulk of its mass is always wet. Only in the less accessible very high névé fields do we find small areas with negligible summer melting. Heavy summer melting is the rule in the accumulation areas of glaciers in the temperate regions. Melt water penetrates deeply into the névé and washes out much of the detail of the record of past precipitation.

We are probably not far wrong in the expectation that the IGY temperate glacier investigations will not give results of a radically new nature; it will mainly deepen our knowledge in an old field of scientific endeavor. We need to know more about how various temperate glaciers react to climate change, particularly how fast and how much.

Polar glaciers—The physics and mechanics of high polar glaciers are much more complicated. High polar glaciers consist predominantly of ice at temperatures below the melting point, and the properties of ice are a strong function of temperature. Furthermore, the two polar glaciers which are mainly being investigated during the IGY, the Antarctic and Greenland ice sheets, are far too large for study as units. We will only see a few small pieces of the perimeter and trace a few lines in the interior. But this is where the new polar glaciology promises a harvest only dreamed of in the past.

Two thirds of the area of the Greenland ice sheet and practically all of the Antarctic ice sheet are permanently dry. All precipitation is in the form of snow. Summer melt is rare and usually affects a surface layer only a few centimeters thick. Thus every snowfall, including everything that fell with it, is, so to say, separately and safely filed for future reference by being buried under later snowfalls.

We were worried about the effect of snow drifting large distances from one place to another until *Swithinbank* [1957] showed that drifting at Maudheim in Antarctica did not carry beyond a few miles. In most places drifting probably only introduces a minor fuzziness into the record; if necessary, its effect could be quantitatively estimated by sampling at the points of a grid.

The first man literally to dig into the files was *Sorge* [1935] of the Wegener Expedition. At 'Eismitte' in Greenland in 1930–31 he excavated a 15-m pit, counted the annual snow layers and determined their density. He also enunciated the most fruitful law of polar glaciology. Sorge's law states that, at any given location in the dry-snow region of a glacier, the density of the snow as a function of depth does not change with time unless the climate changes. During the last few years the records of the snow layers in Greenland have been delved into more deeply and in more detail by means of methods and instruments developed mainly by the U. S. Army Snow Ice and Permafrost Research Establishment (SIPRE). Here also Sorge's law was given mathematical form. The mathematical theory is being further widened to include the effects of changes in rate of precipitation and temperature.

Snow is a poor heat conductor, so that the large amplitude of temperature variation at the surface diminishes rapidly with depth. At ten meters, the annual temperature amplitude is less than $\frac{1}{2}$°C. It is also known, by actual comparison with meteorological records at two locations in Greenland, that this almost constant temperature at ten meters depth is within one degree of the mean annual air temperature. Here then we have a simple means of determining a prime climatic parameter without necessity of long-term meteorological observations. By digging a pit, counting annual layers, and measuring snow density as a function of depth below the surface, the amount of annual precipitation can also be determined. The usual procedure includes digging a pit several meters deep, measuring temperature and noting stratigraphy in the pit wall, and taking closely spaced samples with standard half-liter tubes for density measurements. For samples from a greater depth, a hole is sunk from the bottom of the pit with a hand-operated core drill.

The identification of annual layers can be difficult unless there are thin ice crusts or other features to aid in distinguishing summer from winter layers. In Greenland it is possible to count annual layers almost without error, but the Antarctic summer is much colder and it may be impossible to identify summer layers at high altitudes. In this case Sorge's law suggests two methods for estimating mean annual accumulation, which cannot be discussed here in detail. The first one requires measurement of the rate of snow densification and is based on purely geometrical reasoning; the other is based partly on snow mechanics and is not yet in a satisfactory state. Yet a third new method for distinguishing between winter and summer layers has been developed by S. Epstein (personal communication, 1957) of the California Institute of Technology. It is based on the fact that the ratio of oxygen isotopes 16 and 18 of the snow changes with the temperature at which the snow was formed. This method is apparently very reliable, but requires much expensive laboratory work.

The Greenland and Antarctic snow layers are a treasure trove for the scientist. The tritium content of the snow can, for instance, be determined and used to estimate its age, but only for snow which fell prior to 1954. Since then, the thermonuclear tests have upset the natural tritium balance. F. Begeman (personal communication, 1957) at the University of Chicago determined the tritium content of snow which fell in Greenland in 1954 and found it to be several times greater than normal. Analysis for other radioactive contaminations in precisely dated snow layers from Greenland and Antarctica will yield most valuable data on general atmospheric circulation since the first nuclear devices were detonated in 1945. Scientists who have been monitoring radioactive fallout would now like to go back several years to measure some things they missed at the beginning. The snows of Greenland and Antarctica permit them to do so.

It should furthermore be possible to follow qualitatively and quantitatively the degree of atmospheric contamination by industrial activity by analyses of snows down to the layers which fell in pre-industrial times.

Natural objects which fall with the snow, such as volcanic ash, meteorites, spores, and bacteria, are here perfectly preserved for anybody

who is interested in them. Ash from the Alaskan Katmai volcanic eruption of 1912, for instance, was easily identified in a snow layer from a depth of 32 m below the 1954 snow surface at a point 200 mi east of Thule, Greenland. The relatively high reliability of our identification of annual layers is demonstrated by the fact that we had an error of only one meter, corresponding to two years, at the 1912 level. It is doubtful whether the 1912 dated layer, which is almost certainly continuous over all of Greenland, will be found in the Antarctic, but the ash of the 1883 Krakatoa explosive eruption may prove to be identifiable in both hemispheres. We expect to find it at 50 m depth at the Greenland locality mentioned above and at less than 20 m in Antarctica where precipitation is much lighter.

SIPRE is making a major effort towards successful IGY polar glaciology research. In the summer of 1956 it offered a polar glaciology study course to IGY scientists from the United States, Denmark, France, Germany, Switzerland, Argentina, and Chile. The course was given on a three-week tractor-and-weasel swing from Thule to a point 100 mi out on the Inland Ice. SIPRE also assembled the glaciological instruments which are being used by the glaciological teams of the United States now working in Antarctica (Fig. 1 and 2). The Argentines, British and French are using identical instruments and methods, assuring that comparable data will be obtained from the majority of IGY stations on the Antarctic continent.

The European International Glaciological Expedition to Greenland (EGIG), the Canadian Expedition onto the Northern Ellesmere Island glaciers, the American IGY group in the Brooks Range in Alaska, as well as the SIPRE research group in Greenland will all produce comparable data.

Coring program—The deepest penetration into the past will be done in the US IGY deep-drilling program which has been entrusted to SIPRE. In preparation, SIPRE, in 1956, drilled to 300 m at its experimental station on the Greenland ice sheet some 200 mi east of Thule with the logistic support of the U. S. Army Engineer Arctic Task Force. Core recovery was very incomplete, the primary objective being to develop drilling techniques. Present plans are to drill for a complete four-inch diameter core at the same place in the summer of 1957, then to do the same in Marie Byrd Land in 1957–58, and in 1958–59 at Little America with the logistic support of the US Naval Support Force, Antarctica.

Investigation of cores from the 1956 hole (Fig. 3–5) has revealed that 300 m is very close to the maximum depth for core recovery in any high polar glacier. At the SIPRE laboratories, Langway measured the air content of ice as a function of depth with the following results: As a snow layer is slowly compressed under the ever increasing load of the overlying layers, its permeability decreases to reach zero at a density very close to 0.83. Upon further densification the inclosed air can no longer escape and becomes compressed in the form of numerous small bubbles inclosed in the ice. When the pressure of the overlying snow reaches some 20 kg/cm^2

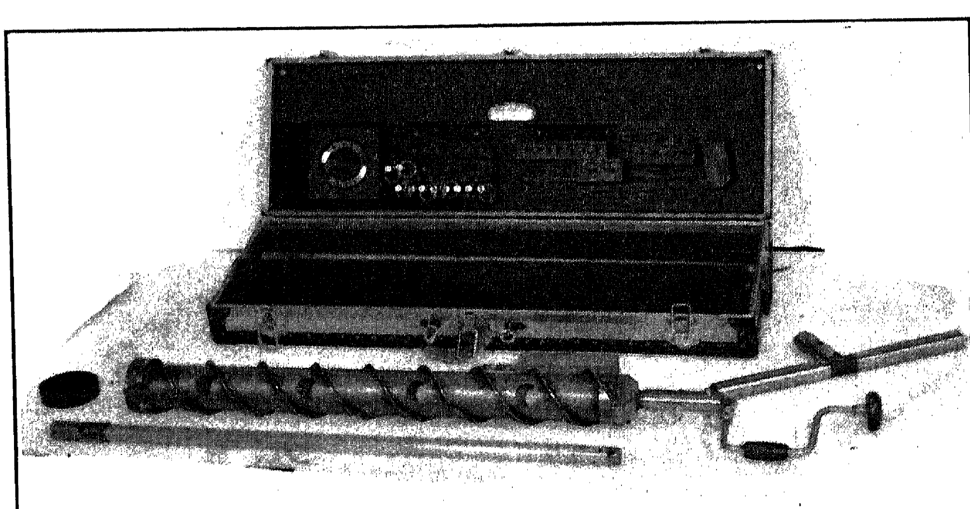

Fig. 1 — USA SIPRE hand coring auger for obtaining three-inch diameter cores of snow and ice; used for coring to a depth of 30 m

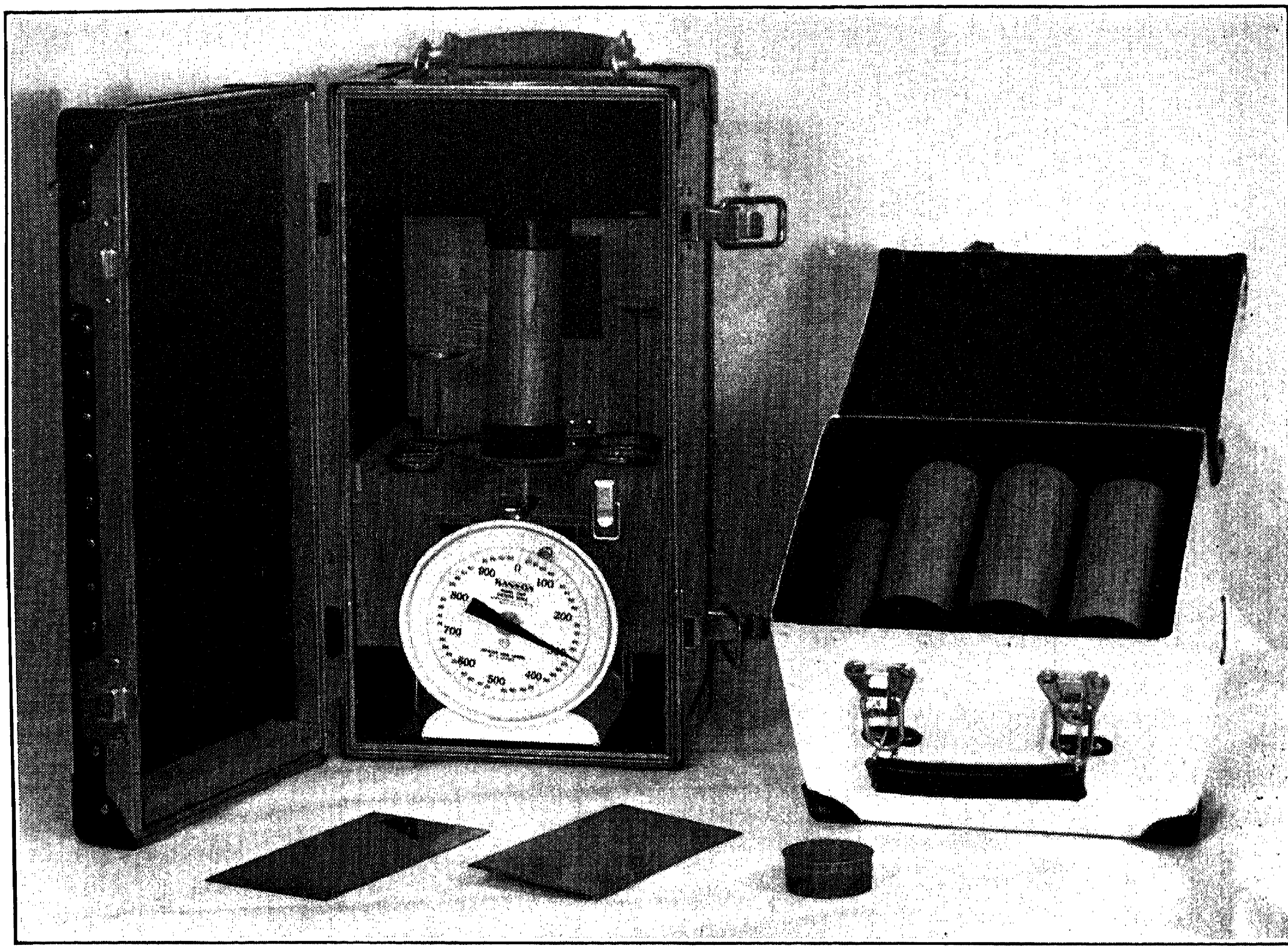

FIG. 2 — SIPRE snow kit for measuring snow density and temperature; consists of half-liter snow tubes, cut-off plates, tube rectifying mandril, spring balance, and dial thermometers

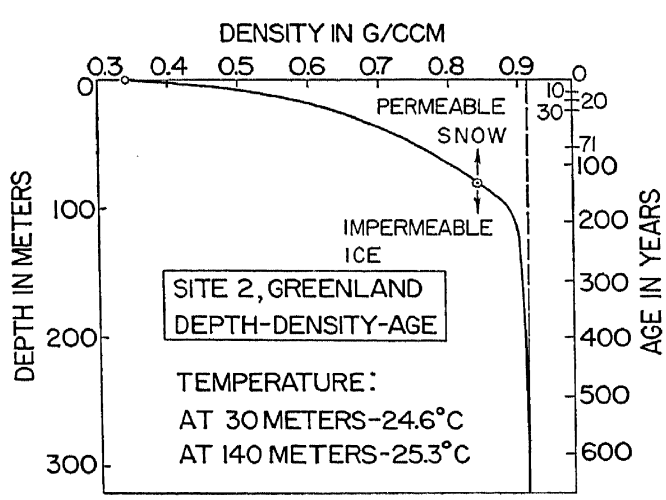

FIG. 3 — Change of snow density with depth on the Greenland Inland Ice, 200 mi east of Thule; the age scale is by actual count of annual layers down to 71 years, and by extrapolation for greater age

at a depth of 230 m, the bubble pressure builds up to 14 kg/cm^2, which is equal to the tensile strength of ice. Since air is used to blow the cuttings out of the drill hole, drilling releases the confining pressure, and both the core and the ice forming the wall of the hole begin to crack when the air bubble pressure exceeds the strength of the ice. Cracking becomes progressively worse with increasing depth. We could drill deeper by using a liquid instead of air, which would prevent collapse of the hole wall, but the cores would disintegrate by bursting of air bubbles on being pulled to the surface. Yet the ability to obtain cores down to 300 m is extremely useful. The age of the snow at that depth at the SIPRE Greenland drill site is nearly 600 years, and in northeast Greenland and Antarctica, where the annual accumulation is much smaller, we may hope to reach back some 2000 years into the past for information otherwise unobtainable.

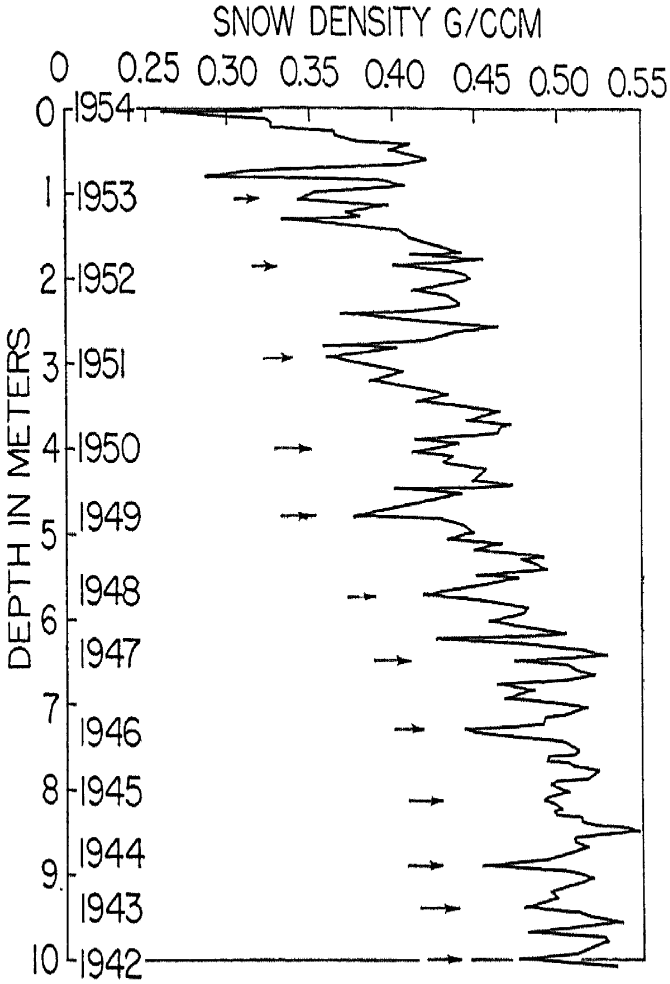

Fig. 4—Change of density with depth as in Fig. 3; detail of upper ten meters; arrows indicate position of estimated midsummer layers of each year; summer layers are generally less dense than winter layers

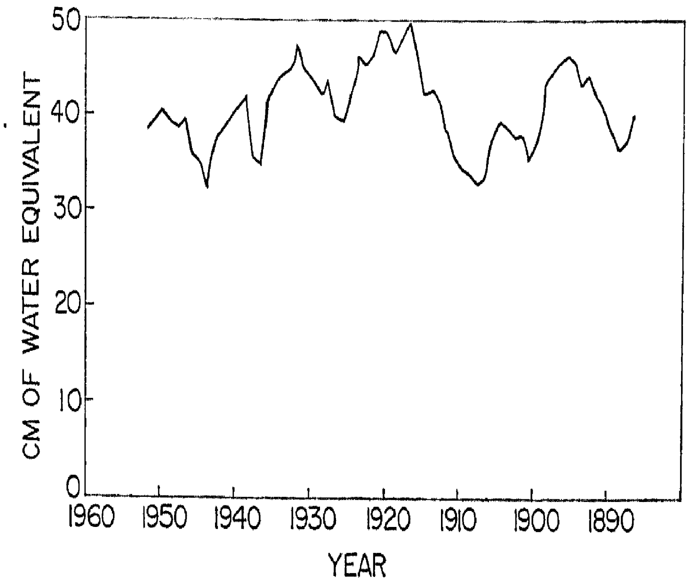

Fig. 5—Five-year running mean of annual accumulation, 200 mi east of Thule, Greenland; estimation of the accumulation of snow in any given year is inaccurate because in measuring the mass between one summer and the next, one does not know whether the summer layers were deposited in June, July, or August; the mean of several years has a much smaller error; the running five-year means show that there is a pronounced cyclic variation in the rate of precipitation, which decreased by more than 20 pct during the last 40 years

There is no doubt that a number of interesting things that could be determined by work on dated ice cores have not yet been suggested. It was therefore decided that the cores will be sliced in half lengthwise and that one-half will be stored in the frozen state for future investigations.

Conclusion—The above account is not a complete exposition of the wealth of new knowledge that will flow from the IGY polar snow and ice studies. Its purpose is to show that this phase of IGY activity is of interest far beyond glaciology in its narrower sense.

References

Sorge, E., Glaziologische Untersuchungen in Eismitte, *Wiss. Erg. Deutschen Groenland Exp. 1929 u. 1930/31*, 3, Brockhaus, Leipzig, 1935.

Swithinbank, C., Norwegian-British-Swedish Antarctic Expedition 1949–52, *Scientific results*, 3, Glaciology I, Norsk Polarinstitut, Oslo, 1957.

Snow, Ice, and Permafrost Research Establishment, Wilmette, Illinois.

Mountain Glaciology

George P. Rigsby

Introduction—Depending upon his objectives, there are several ways in which a scientist looks at glaciers. The glaciologist studies the physics of glaciers and sees them as a study of the accumulation and compaction of snow, the flow or deformation and recrystallization of snow and ice, and its melting and wastage in the lower regions. He frequently needs to work closely with the ice physicist who is interested in the physical and mechanical properties of the substance. The geomorphologist or glacial geologist sees them as a force or agent which changes the landscape as it erodes in one place and deposits in another. He has studied the debris left by the glaciers and, by various means of dating, has established the approximate time of various advancements. The petrologist sees it as a monomineralic metamorphic rock being deformed at the surface of the Earth as it flows to lower elevations. The metamorphic rock he generally studies has been deformed at much too great a depth to ever hope to be able to examine it during the process of metamorphism. Such rock has been brought to the surface only by millions of years of erosion.

The paleoclimatologist sees glaciers as indicators of past climates and has recognized several cycles of advancement and retreat. There have been found four cycles of a duration of several hundred thousand years each which, at their greatest advance, covered almost all of Canada and a large part of the northern United States. Superimposed on these major cycles have been smaller cycles of advancement and retreat, and still smaller cycles on these, making the glacial history difficult to unravel and confusing any prediction as to whether our land surface is likely to be more covered or less covered by ice in a few hundred years from now. There are even minor retreats and advances of no more than a few tens of years which have been observed in our own western mountains. Many theories as to the cause of the ice ages have been proposed, but as yet none has been proved.

The meteorologist is interested in the effects of glaciers and ice caps on the weather, and major efforts to study these interrelationships are now being made in the Antarctic and will continue during IGY. While the micrometeorologist studies the heat budget of the glacier, measuring the incoming and outgoing radiation, the hydrologist is interested in the amount of water stored in the form of ice and the rate of discharge back to the oceans by way of rivers and streams. As can be seen, it is very difficult in many research projects to separate these fields of interest, and indeed, one usually does not want them separated. The balance of this paper is devoted primarily to the objectives of that part of the glaciology program concerning valley glaciers during the International Geophysical Year, which, in its broad aspect, includes most of these fields of interest.

Valley glaciers—The continents today are free of major ice sheets with the exception of Antarctica and Greenland. Still it is estimated that there is enough water locked up in ice sheets and glaciers to raise sea level 150 to 300 ft, which, if released, would inundate a great deal of our rich and heavily populated land areas.

Glaciers are commonly divided into valley glaciers and ice sheets. The term mountain glacier is almost synonymous with valley glacier even though ice caps, which are generally recognized as small ice sheets, are usually found in mountainous areas and are associated with mountain glaciology. The amount of ice in the world outside of the two large ice sheets of Greeland and Antarctica is relatively small, probably being no more than five to ten per cent of the total existing ice.

Glaciers have been geophysically classified by *Ahlmann* [1948] as polar, subpolar, and temperate. The polar glacier is one in which the temperature of the ice is below the freezing point throughout the year with the exception that there may be a small amount of melting at the surface during the summer months. If the melting is great enough to provide runoff on the surface of the ice, but still not raise the internal temperature throughout to the melting point, it might be called subpolar. Temperate glaciers are those which are at the pressure melting tem-

perature throughout the year except that the upper few tens of feet may be lowered below the freezing point during the winter months. This 'frozen' layer is rapidly destroyed in the accumulation zone during the late spring or early summer seasons by the latent heat carried down through the snow and firn by water formed by surface melting. Such a layer, which required the entire winter to freeze to a depth of perhaps 40 or 50 ft by conduction, can be destroyed and brought back to the melting temperature in less than two weeks' time after melting first starts at the surface.

A glacier which does not reach the sea, thereby discharging its ice as icebergs, can be divided into two parts, the accumulation and the wastage or melting areas, which are separated by the firn line. Snow is the usual source of nourishment, which, after becoming one year old, is usually known as firn or névé, and its lower limit is known as the firn line. The farthest retreat of the firn during the season, usually late summer, just before the season's snows begin, is known as the firn limit. The snow, which falls on a glacier and does not melt during the summer season, is gradually buried deeper and deeper each year and compacted until it finally reaches a dense enough state to be called ice; this is arbitrarily set by the glaciologist as the point where the channels are sealed off as air bubbles and water can no longer percolate through. At this stage the specific gravity is usually about 0.82 or 0.83. Because of the thickness of the ice and the slope of the surface on which it rests, the ice flows down hill until it reaches a zone where the conditions are such that the melting on the surface exceeds the winter snowfall, frequently caller the ablation area. It is obvious then that the maximum quantity of ice to flow through any vertical cross section is at the firn limit. Of course, the firn limit fluctuates somewhat from year to year, but, in general, it is a very useful division of the glacier.

Now to get some idea of the present state of a glacier, the total accumulation is measured by digging pits and measuring the average thickness and density of the annual layer deposited during the winter months. Usually the layers of several years can be seen or found in any one location. These layers are frequently separated by somewhat dirty zones caused by an accumulation of dust deposited by the wind and concentrated by melting of the upper surface of the previous winter's accumulation of snow. On ice sheets far from sources of dust, and where there is little if any melting during the summer months, such dirty layers are usually not found, and it becomes much more difficult to distinguish between the annual layers. One must then resort to a study of grain size and orientation and intergrain relationships to separate the layers. S. Epstein of the California Institute of Technology has even been able to distinguish between summer and winter snowfalls by the ratio of the oxygen isotopes in the water molecules, which varies with the temperature at which the snow is formed. Utilizing the average density and thickness measured at selected locations and the area of the firn field, the total accumulation can be calculated. The losses can be calculated by measuring the area and the average thickness of ice lost below the firn line. Sometimes it is feasible to measure the discharge of water at the terminus if the drainage is simple enough and if the total snowfall in the accumulation area is known, in order to calculate the proportion of water lost in that region.

If a glacier is in equilibrium, that is, the accumulation equals the rate of ablation, its total mass will remain the same. In general, with this condition, the glacier remains the same length and the same thickness. If the losses exceed the gains, the firn line moves up the glacier, actually decreasing the area of accumulation, and the glacier will grow thinner and retreat. When the accumulation is greater than the losses, the firn line moves down the glacier, and it thickens and increases in length.

During IGY we are planning to survey by ground and aerial photography as many of the world's mountain glaciers as possible. These pictures will show the location of the terminus and give some idea of the thickness of the glacier. It will help if the firn line also shows in the photographs. Comparison will be made with earlier pictures taken of the same regions and will be available for comparison with pictures taken in the future. In this way, we may be able to deduce some information concerning the part of the cycle which we are now in; that is, demonstrate whether at the present time the region is warming or cooling and whether the precipitation is increasing or decreasing.

We are also very interested in the movement

of glaciers, and, besides measuring the rate of flow along various surface profiles, would like to know more about the flow at depth. Such studies have been attempted by drilling holes and studying their movement and deformation. These and other studies have led to the formulation of ice flow laws which are now being tested in laboratories by several groups of workers in Europe and the United States.

By using seismic reflection shooting, the depth and configuration of the bottom of the glacier is found, and with this knowledge coupled with the flow profile, one can calculate the amount of ice that flows through a specific vertical plane. Taking such a vertical plane through the firn line, one has the total flow of ice from the accumulation area to ablation zone.

Ice, an optically uniaxial mineral, lends itself readily to universal-stage techniques in which the orientation of the optic axis can easily be measured in thin sections and plotted for statistical analysis. During these crystal-orientation studies, impressive fabrics in glacier ice have been found, giving valuable information concerning the way in which the ice is deformed and also leading to information concerning the magnitude and direction of the shear stresses found within the glacier.

There are many other interesting problems being undertaken, such as studies of peat sections, tree growth, soil profiles, and timberline observations, but time will not permit elaboration. However, glaciologists are making the most of the International Geophysical Year to increase our knowledge of glaciers in all parts of the world and in all phases of the field.

Northern hemisphere US-IGY program—On continental North America our most extensive ice fields and ice-covered areas are found along the southern coast of Alaska between Anchorage and Juneau. However, there are glaciers as far north as the Brooks Range in Alaska and as far south as the Sierra Nevadas in California. Our most active programs during IGY on mountain glaciers are on the McCall Glacier in the Brooks Range, Alaska; the Lemon Glacier near Juneau, Alaska; and the Blue Glacier in the Olympic Mountains in the state of Washington, but work is also being done in the Alaska Range, Columbia Icefield, Cascade Mountains, and the Sierra Nevadas.

An extensive program is being carried out in Greenland by the Snow, Ice, and Permafrost Research Establishment of the U. S. Army Corps of Engineers. Their program has the general objectives of the IGY glaciological program, but in some areas of research, such as ice physics, they will go considerably beyond that being done by any other group during IGY.

The principal objectives of the IGY Glaciological program are, of course, much broader than one might be led to believe from the short discussion given above of valley glaciers. Primarily these objectives are: (1) to determine locations, areal extents, and types of glaciers; (2) to determine the pattern of regional climatic trends insofar as they are revealed by observed patterns of present and recent past glacier activity; (3) to determine historical patterns of regional climatic changes insofar as they can be deduced from past glacier fluctuations as evidenced by geomorphological and biological features; and (4) as a prerequisite to interpretation of glacier fluctuations in terms of climatic fluctuations, to investigate the dynamic properties and mass budgets of glaciers, and their relationships to mass and energy exchange between glaciers and their meteorological environments.

The last objective mentioned can be divided into several parts: (a) micrometeorology, (b) glacier mass budget, (c) glacier dynamics, and (d) special studies.

The micrometeorological studies will attempt to measure the mass and energy exchange at the glacier surface and relate this exchange to the glacier mass budget and to the glacier's climatic environment. This will provide one of the most important keys for predicting a change in the glacier regimen which will occur if various climatic parameters undergo some change, and it will also help interpret the history of past glacier fluctuations in these terms.

Continuous measurements will be made of incoming and reflected solar and sky radiation, and net total radiation. The penetration of shortwave radiation into firn, snow, and ice will also be measured by the use of specially designed instruments. Air temperatures and windspeeds at various heights above the glacier surface will be measured along with surface accumulation and ablation. Subsurface temperatures will be measured with thermocouples, thermistors, and thermohms, and thermal conductivity and heat flow will be measured or calculated.

The glacier mass budget will be calculated from the accumulation and ablation measurements. At stations operated throughout the year, the complete history of one season's snow pack will be developed through pit studies.

Analysis of glacier dynamics will require measurements of surface velocity, flow divergence, variation of velocity with depth, and ice thickness.

Additional studies will be made of crevasse patterns and the changes with time in crevasse width, alignment, and down glacier movement. It is hoped that time will permit some additional work to be done in crystallographic and fabric studies and on the metamorphism of snow and ice.

References

Ahlmann, H. W., Glaciological research on the North Atlantic coasts, *R. Geogr. Soc., Res. ser., 1*, 1948.

1432 Carleton Square, San Diego, California

The Crust and Mantle of the Earth*

MAURICE EWING

Two major discontinuities, both nearly spherical, divide the Earth into three parts: mantle, core, and crust, representing 83.3 pct, 16.2 pct, and 0.5 pct respectively of the total volume. From the seismological studies of Wiechert, Oldham, and Gutenberg, we know that the core is fluid, containing an inner core that is probably solid [*Lehmann,* 1936], and that it is separated from the mantle by the sharpest discontinuity within the Earth. From studies of the refraction of compressional and shear waves generated by earthquakes, and also by explosions, we know that the Mohorovicic discontinuity separates the bottom of the crust from the top of the mantle. Modern studies of the dispersion of surface waves of all types are now adding rapidly to our knowledge of the crust and the upper mantle. *Birch* [1951] presented an argument for a change in composition or phase at a depth of about 800 km that has not been conclusively refuted. If this change exists, it is a serious barrier to convection currents.

It has become clear that there is a standard continental crustal section and a standard oceanic one, whose thicknesses are about 35 and 5 km, respectively, which together represent almost the entire surface of the Earth. The areas of exceptional crustal structure are mostly long narrow strips such as the continental margins, the major mountain systems, the mid-ocean ridges, and the island arcs with their associated deep trenches.

There are three major problems about the crust-mantle system which may be considered as the foci of much of present day research. These are (a) the origin of the crust, (b) the mechanics of deformations of the crust, and (c) the possibility of continued interchange of matter between mantle and crust. Rapid progress toward the solution of these problems is being made.

The problem of the origin of the crust is taken to include the question of the separation of the crustal matter from the mantle and the accumulation of the crust into large plates either 5 or 35 km thick over most of the Earth's surface [*Bucher,* 1950]. Two principal lines of thought have been followed. In the first, the segregation of the crustal matter is likened to that of slag on a body of molten metal. For example, *Vening Meinesz* [1957, p. 133] relates both the differentiation and the distribution of the sialic layer to two episodes of convection currents, the first of which occurred at a time when temperatures throughout were high and the Earth could be considered to be fluid. He considers that a first order spherical harmonic convection current brought the nickel-iron to the core and the sialic crustal matter to the surface, sweeping the latter together in an 'Ur continent' in the region of convergence and subsidence of the current. He assumes that an ensuing period of rest was brought on by a combination of two effects: (1) reduction of the thermal gradients below a critical value, and (2) disruption of the flow pattern by accumulation of core material. During the rest period, he considers that the sialic crust solidified into a shell of uniform thickness, covering about one third of the Earth's surface, while the denser mantle remained plastic.

When subsequent current systems occurred, they were confined to the mantle by the presence of the core, and had a considerable number of cells corresponding to higher-order spherical harmonics. These broke apart the 'Ur continent' and transported the fragments to form the present continents in areas of descending currents. During a subsequent rest period, the upper mantle solidified to form the ocean floors. Much of the geophysical evidence gathered in the past quarter century may be interpreted to indicate that mantle convection currents, perhaps further modified in pattern by the solidification of the outer mantle, occur when thermal gradients build up to produce suitable instability.

The other line of thought about origin of the crust may be illustrated in its extreme form by *Wilson's* [1949; 1954, pp. 205–206] suggestion that before the beginning of the geologic era the Earth had a uniform solidified cover of ultrabasic rocks, perhaps overlain by a few kilometers of basalt. Places where this was intruded by or altered to granites or granodiorites gradually

* Contribution No. 300, Lamont Geological Observatory, Columbia University.

formed the small nuclei of continents. Tuffs, conglomerates, and graywackes collected on the nuclei, and erosion produced such sediments as sandstones and limestones which accumulated around the margins. These accumulations acted as centers for systems of off-shore fractures along which rose hot gases, solutions and predominately acidic lavas. These contributed to the growth of the atmosphere, the oceans, and the continents according to a pattern which is considered to have persisted, and to be expanding the continents at the present time. *Stille* [1934, 1941] considered that continents grow by repeated addition of the consolidated rocks of peripheral orthogeosynclinal belts to earlier cratons. *Kay* [1951, p. 103] concludes that the "stratigraphic evidence supports a theory that continents have grown interruptedly by reduction of oceanic areas through an intermediate island-arc stage."

Mechanisms of deformation of the crust—Deformations of the crust can only be studied properly by taking full account of the accompanying deformations of the upper mantle. Perhaps the simplest deformations are isostatic and tidal. These deformations are controlled primarily by properties of the mantle rather than those of the crust, hence can yield data primarily relating to the mantle. Calculations of mechanical properties of the upper mantle from the recent uplift of the Baltic and Canadian Shields, considered solely on isostatic readjustment following melting of the Quaternary ice caps, are well-known [*Haskell*, 1936; *Vening Meinesz*, 1937, 1954; *Gutenberg*, 1941, 1942]. *Stille* [1955, p. 173] pointed out the probability that crustal warping resulting from causes other than ice loading are in progress, and that "post-glacial isostasy should rather be considered as an additional factor in the general concept of unwarping." Sedimentation, erosion, and changes in sea level all produce isostatic crustal adjustments which are difficult to isolate from vertical displacements that result from other causes.

A second type of deformation, which is also amenable to calculation, is that imposed by the polar flattening of the spheroid during a shift of the crust relative to the axis of rotation. *Vening Meinesz* [1947] has shown that a pole-shift can be chosen which will yield a shear pattern closely related to topography and tectonic pattern of the ocean basins and the margins. He shows a correlation between the calculated shear pattern and the distribution of geophysical phenomena such as gravity anomalies, seismicity, and volcanism in selected areas. Similarities of the calculated shear pattern to the tectonic patterns given by geologists were found for many continental areas.

Many details of the crustal deformations which occur in mountain building are known through geological and geophysical studies. But there is no generally accepted explanation of the fundamental cause of mountain building, hence there is no immediate prospect for a quantitative theory for this type of crustal deformation. It is generally agreed that in the first stage a long narrow trench, say 200 mi wide and 5000 to 15,000 ft deep, formed and is filled with sediment. In practically all mountain systems of the Earth, it appears that compression of the crust in a direction normal to the length of the trench, has buckled and sheared the sedimentary beds. *Bucher* [1955, 1956] has suggested that gravitational sliding of the accumulated sediments may produce an impression that the crustal shortening is far in excess of its actual value. Invasion, either by great volumes of granitic magma or by heated gases and solutions which melt the sedimentary rocks and convert them to granites, occurred in some cases on a very large scale to produce great batholiths as in the Sierra Nevada. In other cases, the intrusive bodies and the metamorphised sediments are small and relatively insignificant, as in the Rocky Mountains proper. The elevation which accompanies and follows the intrusive stage completes the building of the mountain range.

Mountain building, as described above, has been confined to the continents, usually near the margins, or to island-arc structures which likewise are generally near the continental margins. The absence of mountain building in the ocean basins throughout geologic time is a striking and significant fact.

The Mid-Atlantic Ridge, and other ridges of similar type, do not form exceptions to the statement just made. It has been pointed out by *Ewing* and *Heezen* [1956, pp. 78-80] that this ridge continues through the Arctic, Indian, and Pacific Oceans, and that a median rift zone is a characteristic feature. The rift zone accurately follows the continuous narrow belt of shallow-focus earthquakes which provides a basis for predicting continuity of the ridge-rift structure through areas where soundings are inadequate or lacking. It is concluded that the rift zones of East Africa and South Island, New

Zealand, are landward extensions of the mid-ocean rift system, that the rifts result from tension in the crust and that the seismicity indicates present-day motion of the rift. Seismic refraction results reported by *Ewing* and *Ewing* [in press] give the following information about the Mid-Atlantic Ridge: sediments, >1 km thick, $v=1.7$ km/sec; basaltic volcanics, ± 3 km thick, $v=5.2$ km/sec; and mantle-basalt mixture >30 km thick, $v=7.2$ km/sec.

The actual thickness of the last layer has not been measured, nor has the seismic wave velocity in the underlying mantle. The designation of the last layer as 'mantle-basalt mix' is based on two facts. The velocity 7.2 km/sec is intermediate between the typical mantle velocity of 8.1 km/sec, and the oceanic crustal velocity of 6.7 km/sec. The igneous rocks dredged from the Mid-Atlantic Ridge or brought to the surface by the volcanoes are mostly basalts, peridotites, and serpentines [*Shand,* 1949]. It is concluded that ascending mid-ocean mantle convection currents provide the tensional forces to produce the rift and that these currents have also supplied and segregated the large quantity of basalt which is found in the mid-ocean ridge system. Thus the mid-ocean ridges are entirely different in structure and in origin from the cordillera, to which they have at times been compared.

The ultimate driving force that is responsible for the major deformations of the Earth's outer layers and the mechanism through which it acts must still be sought. Brief discussions of many of the suggested mechanisms have been given by *Eardley* [1957] in an account which shows that the geologists are no less puzzled than the geophysicists about this fundamental problem. Are the forces merely the stresses resulting from cooling? May we consider the machine as a heat engine? Is the energy chemical, gravitational, or thermal? Whatever the nature of the energy reservoir there is a continual drain on it for various thermal processes as well as for the mechanical deformations. Ultimately the supply of available energy must be depleted. There is no clear evidence of a decrease in the rate of the various geologic processes, hence the terrestrial reservoir of available driving energy must be large compared with the total drain throughout geologic history.

An earthquake is the result of fracturing during deformation of the crust and upper mantle. The seismic energy radiated as waves of various types was accumulated gradually as strain energy and released by rupture. Investigation of the action at the earthquake focus thus is one of the most direct means of obtaining information about the deformations which are occurring at the present time. Important studies are in progress on several phases of this problem as follows: (a) maximum energy released in individual shocks; (b) total volume strained, as determined by the spatial distribution of aftershocks; (c) rate of energy accumulation and release in a single fault system; (d) position, inclination, and extent of fault, and direction of motion on the fault from instrumental and field studies of single shocks; (e) cumulative motion along fault during recent geological time evaluated from field studies on exposed faults and compared with result from studies of present day shocks on the same faults; (f) relating of surface waves and tsunami generation to action at the focus; amplitudes, frequency spectra, and directional properties of the source.

For all of the instrumental parts of this program the requirement is a suitable wide geographical distribution of seismograph installations, each capable of recording all wave types over a broad range of wave periods. Of great importance is the discovery by *Benioff* [1951, 1955] that all of the great shocks of the Earth are related through a single stress system.

In addition to the information on action at the focus, seismology can provide precise data on the structure of the crust and upper mantle through propagation studies. These are treated by *Oliver* [1958].

Explosion seismology has been the principal source of our knowledge of the crust and of the outer mantle. Until recently the application of this powerful method has been limited to small explosive charges used specifically for seismic surveys, or to observations of somewhat larger charges, such as those used in quarries and open pit mines. These offer the great advantage that origin time, epicenter coordinates, and depth of focus may be accurately known, but lack the energy required for probing deeper than the topmost part of the mantle. Nuclear explosions resulting from bomb test programs opened the possibility of improved body-wave investigations to all depths, as illustrated by *Bullen* and *Burke-Gaffney* [1957ab, 1958] in an excellent contribution to the difficult problem of waves through the inner core and diffracted PKP phases. These explosions also have permitted new studies of surface wave generation and propagation

[*Oliver* and *Ewing*, in press]. (Data on 15 such explosions from three test areas were released by the United States Atomic Energy Commission April 15, 1958. These data are of fundamental importance to seismologists, and have stimulated many seismological studies, several of which are already in press. Similar data for representative tests from other test areas are badly needed.)

The numerous recent geothermal investigations, particularly in ocean sediments, give promise of a new insight into thermal and mechanical processes on the upper mantle. The many measurements of remanent magnetization of rocks from many parts of the Earth are interpreted by many workers to require continental drifting on a large scale. Excellent work in age determinations is making significant changes in our ideas on the absolute and relative ages of various parts of the Earth's crust. The fact that pre-Cretaceous sediments have not yet been found in the ocean basins has evoked suggestions that all older sediments have been engulfed in the mantle. Further developments in any one of these fields can lead to radical changes in our concepts of crustal and mantle mechanics. But at the present time it is very difficult to judge which of the new results must be accommodated into our structure of geophysical knowledge, perhaps to reveal the ultimate driving force that deforms the outer mantle and crust, and which must be reexamined, reinterpreted and perhaps rejected.

References

Benioff, H., Global strain accumulation and release as revealed by great earthquakes, *Bul. Geol. Soc. Amer.*, 62, 331–338, 1951.

Benioff, H., Seismic evidence for crustal structure and tectonic activity in the crust of the Earth, *Geol. Soc. Amer. spec. pap. 62*, pp. 61–73, 1955.

Birch, F., Remarks on the structure of the mantle, and its bearing upon the possibility of convection currents, *Trans. Amer. Geophys. Union*, 32, 533–535, 1951.

Bucher, W. H., Megatectonics and geophysics, *Trans. Amer. Geophys. Union*, 31, 495–507, 1950.

Bucher, W. H., Deformation in orogenic belts, crust of the Earth, *Geol. Soc. Amer. spec. pap. 62*, pp. 343–368, 1955.

Bucher, W. H., Role of gravity in orogenesis, *Bul. Geol. Soc. Amer.*, 67, 1295–1318, 1956.

Bullen, K. E., and T. N. Burke-Gaffney, Evidence relating to the Earth's inner core from hydrogen bomb explosions in 1954, *Nature*, 180, 49–50, 1957a.

Bullen, K. E., and T. N. Burke-Gaffney, Seismological and related aspects of the 1954 hydrogen bomb explosions, *Austral J. Phys.*, 10, 130–136, 1957b.

Bullen, K. E., and T. N. Burke-Gaffney, Diffracted seismic waves near the PKP caustic, *Geophys. J.*, 1, 9–17, 1958.

Eardley, A. J., The cause of mountain building, an enigma, *Amer. Scientist*, 45, 189–217, 1957.

Ewing, M., and B. C. Heezen, Some problems of Antarctic submarine geology, *Antarctica and the International Geophysical Year*, Geophys. Monograph 1, Amer. Geophys. Union, pp. 75-81, 1956.

Ewing, J., and M. Ewing, Seismic refraction measurements in the Atlantic ocean basins, in the Mediterranean Sea, on the Mid-Atlantic Ridge, and in the Norwegian Sea, *Bul. Geol. Soc. Amer.*, in press.

Gutenberg, B., Changes in sea level, post-glacial uplift, and mobility of the Earth's interior, *Bul. Geol. Soc. Amer.*, 52, 721–772, 1941.

Gutenberg, B., Is the land around Hudson Bay at present rising? *Amer. J. Sci.*, 240, 147–149, 1942.

Haskell, N. W., The motion of a viscous fluid under a surface load, II, *Physics*, 7, 56–61, 1936.

Kay, M., North American geosynclines, *Geol. Soc. Amer. Mem. 48*, 1951.

Lehmann, I., P′, *Pub. Bur. Cent. Seism. Internat.*, ser. A, 14, 1936.

Oliver, J., Seismology and the IGY, *Geophysics and the IGY*, Geophys. Monograph 2, Amer. Geophys. Union, 190–197, 1958.

Oliver, J., and M. Ewing, Seismic surface waves at Palisades from explosions in Nevada and in the Marshall Islands, *Proc. Nat. Acad. Sci.*, in press.

Shand, S. J., Rocks of the Mid-Atlantic Ridge, *J. Geol.*, 57, 89–92, 1949.

Stille, H., The growth and decay of continents, *Research and Progress*, 1, 9–14, 1934.

Stille, H., *Einfuhrung in den Bau Amerikas*, Borntraeger, Berlin, 1941.

Stille, H., Recent deformations of the Earth's crust in the light of those of earlier epochs, *Geol. Soc. Amer. spec. pap. 62*, pp. 171–192, 1955.

Vening Meinesz, F. A., The determination of the Earth's plasticity from the postglacial uplift in Scandinavia; isostatic adjustment, *Proc. K. Nederl. Akad. Wetensch.*, ser. B, pp. 654–662, 1937.

Vening Meinesz, F. A., Shear patterns of the Earth's crust, *Trans. Amer. Geophys. Union*, 28, 1–61, 1947.

Vening Meinesz, F. A., Earth crust movements in the Netherlands resulting from Fennoscandian postglacial isostatic readjustments and Alpine foreland rising, *Proc. K. Nederl. Akad. Wetensch.*, ser. B 57, pp. 142–155, 1954.

Vening Meinesz, F. A., The geophysical history of a geosyncline, I, *Proc. K. Nederl. Akad. Wetensch., ser. B*, 60, 126–140, 1957.

Wilson, J. Tuzo, An extension of Lake's hypothesis concerning mountain and island arcs, *Nature*, 164, 147–148, 1949.

Wilson, J. Tuzo, The development and structure of the crust, *The Earth as a planet*, G. P. Kuiper, ed., Chicago Univ. Press, 1954.

Lamont Geological Observatory, Columbia University, Palisades, New York.

Seismology and the IGY *

JACK OLIVER

Introduction—The purpose of this paper is to give a brief survey of the methods, achievements, and potentialities of the field of seismology to serve as a background for the seimological program of the International Geophysical Year. Hence the following discussion will be limited to the topics of seismology which relate especially to that program. These are (1) seismicity, essentially the geography of earthquakes; (2) earthquake mechanisms; (3) seismic-wave propagation and exploration of the Earth's interior; and (4) microseisms, the minute tremors of the Earth present at all times at all places. Other topics of less pertinence to the IGY which are not discussed include (1) macroseismology, the study of the intensity of earthquake effects near the epicenter; (2) engineering seismology, the study of problems of an engineering nature, primarily construction, in seismic areas; and (3) seismic prospecting, the application of the methods of seismology to the search for minerals.

Seismicity—Modern studies of seismicity on a global scale depend primarily on locations of earthquake foci and on magnitudes of shocks based on instrumental data, for although historical records are at times of considerable value, their strong dependence on density of population and type of civilization makes precise quantitative studies impossible. Let us examine the instrumental methods of location and magnitude determination in use today.

Seismograph stations, at present, are distributed throughout the world in a pattern which is highly dependent on population and, of course, topography. Except for a few island stations, the vast oceanic areas are complete blanks in the seismic-data map.

When a sufficiently large earthquake occurs, each operating station records ground motion as a function of absolute time. These records consist of a number of identifiable waves corresponding to propagation through the interior of the Earth as compressional (P) or shear (S) waves, or as reflected or refracted combinations of both types or both, and to propagation as surface waves in the superficial layers. The pattern composed of the various wave types at a given station depends on the travel times of the waves and on the distance of the station from the epicenter. With such data from many stations, the essential information required for a precise epicentral location is the travel time for each wave as a function of distance. Approximately the first forty years of instrumental seismology were required to fix this relationship, in the case of the principal phases, within the limits of experimental error. Now that this relationship is available, however, the station seismologist is able to find the approximate location of the earthquake, interpret his record, and forward the data to a central agency where information from all stations is combined to fix the focus of the quake more precisely in time and space. With reasonably good data, an epicenter can be located to within ¼ to ½ degree in distance, 25 to 50 km in depth, and about five to ten seconds in time. With exceptionally good data this can be improved upon, whereas with poor data less accuracy is obtained and in the extreme case no location is possible. To some extent the quality of the data is dependent upon the magnitude of the shock and there must be countless shocks of small magnitude which go undetected because they are beyond the range of existing seismographs, but except in cases where special knowledge of the seismicity of an area is required, this omission is not serious. Unfortunately, however, with the present distribution of stations, this gap in our knowledge is not restricted to minor shocks; many earthquakes of appreciable magnitude are poorly located for lack of data and possibly many more go undetected.

Let us review the Earth's seismicity with these problems of detection and location in mind and using the conventional definitions for depths; that is, shallow, less than 70 km; intermediate, 70 to 300 km; and deep, 300 to 700 km. The Earth may be divided into relatively inactive blocks separated by active zones (Fig. 1) [*Gutenberg* and *Richter*, 1954]. The most im-

* Lamont Geological Observatory Contribution No. 255.

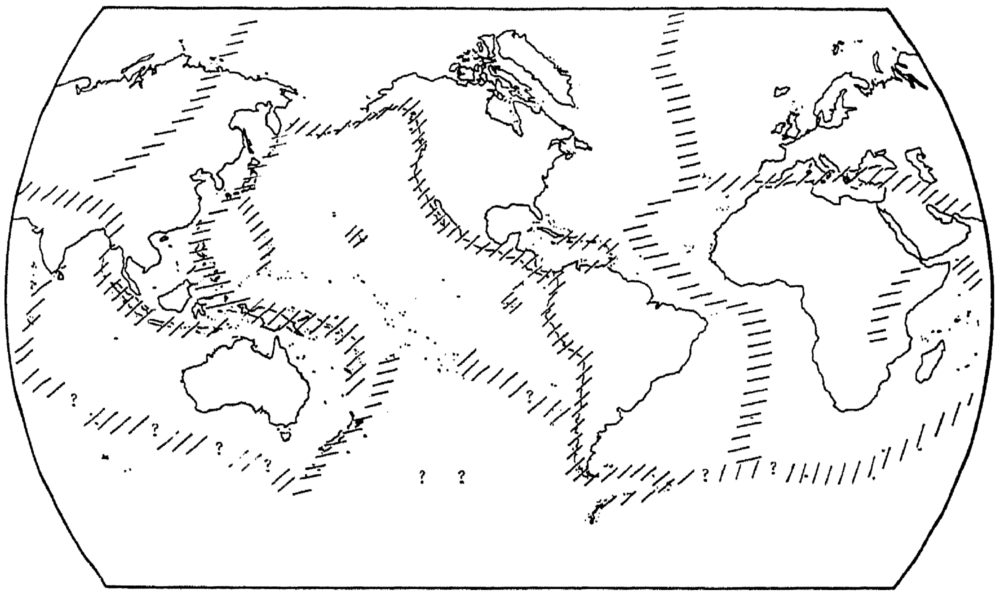

FIG. 1 — Seismic zones

portant of these by far is the circum-Pacific zone which accounts for about 80 pct of shallow shocks, 90 pct of intermediate shocks, and virtually all deep shocks. This belt circles the Pacific, in general, but has several branches which include the West Indies, the Southern Antilles, and the Sunda arc. Almost all remaining shallow shocks and all of intermediate depth are included in the Mediterranean and trans-Asiatic zones. Shallow shocks of moderate intensity are associated with topographic ridges in the Arctic, Atlantic, Pacific, and Indian oceans and with supposed rift structures such as those in Africa and the Hawaiian Islands.

The great gaps in our knowledge of seismicity lie principally in the Southern Hemisphere because of the low density of seismographs there. Antarctica appears to be a relatively stable area but knowledge of small shocks is very limited [*Gutenberg* and *Richter*, 1954]. As pointed out by Gutenberg and Richter, belts of minor seismicity in the Antarctic take on unusual importance as clues to the geology underlying the icecap. Additional knowledge of areas which are known to be seismic but for which limited data are available, such as the Southern Antilles and Indian and Southern Atlantic Ocean belts, is highly desirable.

Many attempts to delineate the 'fracture zones' of the Earth's crust by tracing seismic belts around the Earth have been made; in a recent one [*Ewing* and *Heezen*, 1956], some of these belts were connected with a topographic rift feature in submarine mountain ranges. All of these attempts have experienced difficulty with continuity of the zones through the southern hemisphere because of poor information on seismicity. Clearly, an addition to such an important facet of global geology is worthwhile.

An equally important branch of seismicity concerns the quantity of energy released, both by individual shocks and as a function of time and location. Unfortunately, many factors such as instrumental difficulties, radiation patterns, and the vagaries of wave transmission in the Earth, combine to make this study quite difficult and even the most enthusiastic seismologist would not claim accuracy greater than a factor of ten for such studies at present. However, the amount of energy released by earthquakes as well as the rate at which it is released is of fundamental importance to the study of physics of the Earth and continued effort in the field is essential. Improved instrumentation during the IGY plus greater international cooperation should aid this effort.

Benioff [1955] has concluded from studies of strain release in great shocks that these shocks are related in a single stress-strain system. The increased world-wide seismicity following the large Aleutian shock of March 9, 1957, when studied in detail, may result in a confirmation and extension of this view. Benioff has also pioneered in the development of strain meters which measure, in addition to seismic waves, long-period deformation of the crust. Such deformation has also been measured by surveying methods, particularly by the Japa-

nese. During the IGY, strain measurements will be extended by the United States to the active tectonic belts of South America.

Earthquake mechanisms—Throughout the years, many mechanisms have been proposed to account for the sudden release of energy during an earthquake. These have included explosions, implosions, collapse of lava chambers, etc. It now appears that, for shocks of appreciable magnitude, the elastic rebound theory is most nearly correct. This theory assumes that strain accumulates gradually in a given volume of rock and then is released catastrophically when a rupture or, perhaps more commonly, slippage along an existing fault occurs.

Such a mechanism would result in a characteristic pattern of first motions of seismic waves over the surface of the Earth [*Byerly*, 1955]. Conversely, if this pattern can be measured, the fault orientation and direction of motion can be deduced. This work has been pioneered by Byerly and Nakano and carried out in some volume by Hodgson, Ritsema and others, including several Russian seismologists [*Hodgson*, 1957]. Unfortunately, if only the initial motion of the P wave is used, the results are ambiguous and two solutions are possible, the possible fault planes being mutually perpendicular. This ambiguity may be resolved theoretically through the use of shear-wave data, and such attempts have been made, notably by the Russians. However, the interpretation of initial shear-wave motion is frequently nebulous, and the published results are somewhat suspect on these grounds. Over 100 shocks have been examined by the fault-plane method in one form or another, and roughly 10 per cent of these have been checked with observed surface displacement with encouraging agreement.

Approximately 90 pct of the shallow shocks studied to date have a strike-slip component of motion greater than the dip-slip component. This is a surprising result in view of the apparent preponderance of observations of normal and reverse faults throughout the world. Geologists, in general, have taken little notice of these results but as the evidence continues to accumulate it appears more and more likely that a fundamental change in our concept of some tectonic processes may be forthcoming.

Since data must be obtained from many seismograph stations widely distributed throughout the world for any given fault-plane solution, this topic, like seismicity, is fundamentally international in character, requiring close cooperation with seismologists everywhere. The IGY should provide a stimulus to the circulation of the required data. Certainly the fault-plane work is of great importance and although present results are for shocks generally scattered about the world, a logical extension (already attempted in the East Indies by *Ritsema* [1957]) of the program is a detailed study of the motion from many shocks in the same region, particularly one in which deep shocks are found.

Seismic wave propagation and exploration of the interior of the Earth—The travel-time curves for body phases, described in the section on seismicity, serve not only to locate earthquake foci, but also provide the bulk of man's knowledge of the interior of the Earth.

The velocity v either compressional or shear as a function of the radius, r, may be found from an integral equation, the solution of which is generally credited to Herglotz and Bateman [*Bullen*, 1953]. Formal limitations of the method are that the gradient of v with respect to depth cannot be less than $-v/r$, and v cannot change abnormally rapidly without affecting the result. Furthermore, uncertainties in the travel time data are, of course, reflected in the final result.

The velocities of compressional waves V_p and shear waves V_s depend on the elastic constants in the following manner

$$V_p = \left(\frac{k + \frac{4}{3}}{\rho}\right)^{1/2} \qquad V_s = \left(\frac{\mu}{\rho}\right)^{1/2}$$

where k and μ are the incompressibility and rigidity respectively and ρ the density.

Assuming hydrostatic pressure $dP = -g\rho dr$

$$d\rho/dr = -g\rho/(V_p^2 - 4V_s^2/3)$$

where g is the acceleration at r. This is the well-known Adams-Williamson equation. Knowing the velocities as a function of depth, this equation gives the density as a function of depth providing certain limiting values are known.

Investigations based primarily on this method have led *Bullen* [1954, 1955] to divide the Earth into seven spherically symmetrical regions named A through G. A is the Earth's crust of about 40 km maximum thickness and will be discussed in some detail later. B is the upper part of the mantle and extends to a depth of about 400 km,

the so-called 20° discontinuity. Here the velocity gradients apparently change sharply. In region C, the velocity gradients decrease slowly to about 1000 km and then remain steady in layer D to the base of the mantle. The boundary of the core is at a depth of 2900 km. No shear waves have been detected through the core, and partly because of this apparent lack of rigidity, which confirms other data from Earth tides and latitude variation, the core has been called 'liquid.' At almost 5000 km there is a thin transition layer F, about 150 km thick, and from the base to the center of the Earth is the inner core, region G.

There are many controversial aspects to this model which need to be resolved, a few of which are cited here. *Gutenberg* [1954], on the basis of amplitudes of P and S waves, travel times from deep earthquakes, and 'channel' waves, believes a low velocity channel is present in the asthenosphere in region B. The nature of the 20° discontinuity between B and C has been the subject of many papers but has not been fully resolved. The transition zones at the base of the mantle and at the base of the outer core need attention. Several papers have been written on the possible rigidity of the inner core but the experimental data on shear-wave transmission through this zone are inconclusive. With improved instrumentation, improved time standards, more precise epicentral locations and focal depths, new sites for seismographs, and the use of amplitudes and frequency spectra of seismic body waves in addition to the conventional arrival time, there is every reason to believe that seismic data will provide much new and important information on the interior of the Earth.

Region A, the crust, plus the upper part of the mantle is of special interest because of its intimate relationship to surface geology. At depths beyond the range of drilling, seismology again provides a large portion of our information on structure and composition. Seismic investigations of this region may be divided into two classes, (1) those involving refraction and reflection of body waves, a technique essentially similar to that used for deeper regions, except that man-made explosions may be used as sources of energy in addition to rockbursts and earthquakes; and (2) surface-wave studies.

When the body-wave technique is applied to oceanic areas, explosive sources are used almost exclusively, limiting the range which may be explored to about 50 or 100 mi, and the depth to about 15 to 20 km. Fortunately, the mantle is very shallow beneath the deep oceans, about 10 to 12 km, and the entire crust can be examined. This crust, in a typical structural column, might be five kilometers in thickness with a velocity about that of the deeper part of the continental crust. A thin layer of sediments, about one kilometer thick, overlies this crust and in some cases, particularly in the Pacific, another thin layer, possibly volcanics, lies beneath the sediments. Problem areas of geologic importance within the capability of the seismic method at sea include (1) studies of the transition region between continental and oceanic crust; (2) detailed studies of major structures such as the island arcs, island platforms, and submarine mountain ranges; (3) investigation of sedimentation and lithification processes from detailed studies of sub-bottom materials. The latter depends upon the development of the long-awaited ocean-bottom seismometer, currently in the testing stage.

On land, results from quarry blast data, which have the advantage of precise timing but are restricted to sources at the surface only, and near earthquake and rockburst data, for which the reverse are true, have been generally concordant with a few discrepancies. A typical continental crustal column would consist of about 35 km of rock in which the velocity increased gradually, or in one or two discrete jumps, with depth in the crust, with an abrupt increase at the top of the mantle. *Gutenberg* [1954] has suggested that a low-velocity layer in the crust would explain the discrepancies between blast and earthquake results. Such a layer would be undetectable by ordinary explosion techniques. One difficulty in correlating the results of both types of data is that near earthquake studies are always made, of necessity, in regions where the crust is very likely anomalous, and, hence, the results are not typical of other less disturbed regions. A surprising result of the refraction technique is the small thickness obtained for the crust beneath the Colorado plateau by *Tatel* and *Tuve* [1955] and similarly in the Transvaal by *Gane* and others [1956]. Gravity studies indicate that the crust should thicken in accordance with the increased elevation in these regions. This difficulty needs to be resolved by further seismological and gravitational studies to verify the results. If they are proven to be typical of

the region rather than anomalous, then it may be necessary to assume a non-homogeneous mantle, that is, one with lateral variations of density, to account for the discrepancy.

Investigations of the crust and mantle by surface-wave techniques usually apply to distances of the order of thousands of kilometers rather than hundreds as in the case of artificial explosions [*Ewing* and *Press,* 1956]. Hence the structures deduced for the crust are average ones for areas of continental dimensions. Results are based primarily on the dispersion of surface waves, that is, the dependence of phase and group velocity on wave length. Two principal types of surface waves, named after their discoverers, Love and Rayleigh, are known and may be recognized by their different particle motions. A composite curve, group velocity versus period, for Rayleigh-type waves is shown in Figure 2. Waves of great length, that is, having periods of 75 sec or greater, cannot resolve the difference between oceanic and continental crusts and derive their properties primarily from the mantle. In fact, the longest of them may be affected by the non-rigid core. For waves of periods less than 75 sec the dispersion curves depend greatly on the structure of the crust. The ocean branch continues at a high velocity for some time because of the shallow mantle, but drops rapidly when the waves become short enough to be controlled primarily by the water layer. The continental branch drops in velocity fairly quickly because of the greater depth of the mantle, but flattens again because of the small contrast between the continental rocks over the entire depth range. Prior to the past year, dispersion of waves of periods shorter than about ten seconds was difficult to interpret in terms of crustal structure. However, recent identification of higher modes for continental paths has not only permitted the unravelling of the complicated train of continental surface waves, but has significantly increased the potential of the surface wave technique for crustal exploration. The striking success of the normal mode theory in the explanation of a major portion of seismic-wave energy from a distant shock makes this a method of fundamental importance to seismology.

The surface-wave results are, in general, in accord with those of blast and near earthquake data. There is, however, at present no good indication of a low-velocity layer within the crust from the surface-wave data and the precision to which the dispersion is now known puts rather strict limitations on any deviation from the relatively simple crustal structure in which the velocity increases gradually or in small discrete steps with depth. More precise crustal structures will be forthcoming from the surface-wave data when adequate theoretical computations are available, once a long and difficult task. Application of high-speed computing devices to the problem promises to remedy this situation within the next year.

Many significant problems are available to

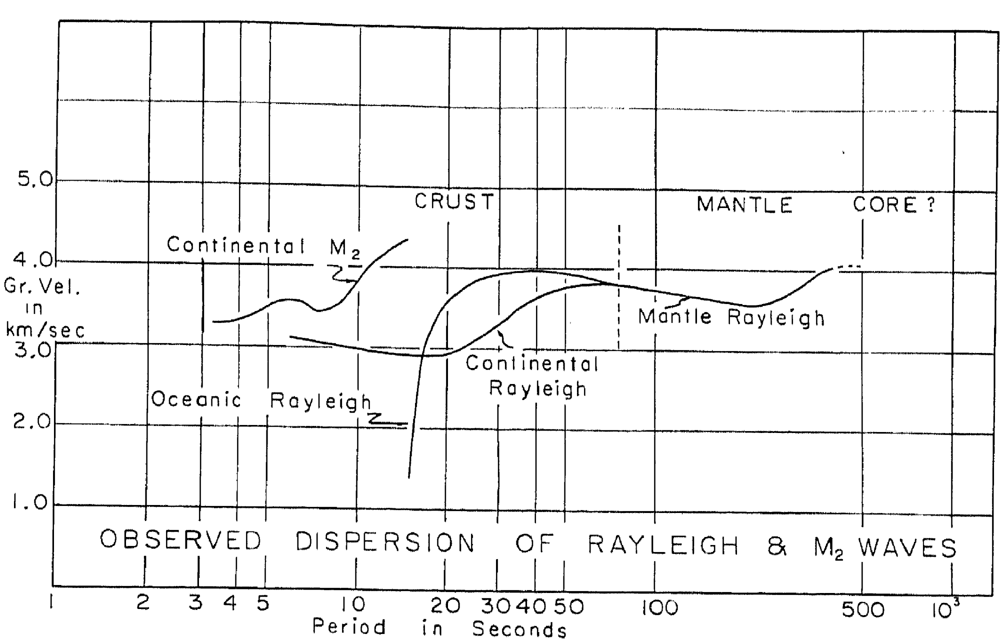

FIG. 2—Rayleigh wave dispersion

the student of surface wave seismology. The dispersion curves shown in Figure 2 and the similar curves for waves of the Love type have gaps that are immediately evident at both the long and short period ends. The M_2 curve needs additional work.

The limit at the long-period end of the seismic spectrum would appear to be the fundamental resonance of the Earth as a whole. Theoretical calculations, possibly verified experimentally in one case by *Benioff* and others [1954], indicate periods of the order of one hour for this effect. The short-period limit to which dispersion studies may be pushed would appear to depend on the inhomogeneities in the crust, already evident to some extent. Studies of excitation of surface waves may provide additional information on fault mechanisms, fault extent and orientation and focal depth.

Another surface-wave technique concerns phase velocity, rather than group velocity, and may be obtained by measuring the velocity of a wave between two stations, a method pioneered by *Press* [1956]. The section of the crust explored is much smaller in extent than in the usual group velocity situation. This method has been used with some success in California where the density of seismograph stations is high. The technique appears to have great potential but at present involves some assumptions about the velocity structure of the crustal column and the effect of dip and crustal irregularities which need further consideration before reliable, absolute values for crustal thickness can be obtained regularly.

The long-period and Lg seismology programs of the IGY are designed to provide better surface-wave data. The long-period instruments (seismometer period $T_o=15$ to 30 sec, galvanometer period, $T_g=90$ to 100 sec) are the type which recorded almost all of the long period data of Figure 2. The Lg instruments ($T_o=$ 15 sec, $T_g=8$ sec) will record waves of the higher modes and short-period segments of the fundamentals best. The vertical-component seismometer is manufactured by the Sprengnether Instrument Co. (Fig. 3), as are the recording drums. The horizontal component seismometers and the long-period galvanometers are made by Lehner and Griffiths. Response curves of both the LP and Lg types of seismographs are shown in Figure 4.

Microseisms—With present-day seismographs there is little difficulty in obtaining adequate amplification of ground motion and so the gain is limited primarily by the amount of background noise. This noise, for most seismographs, generally falls in the period range of about ½ to 9 seconds, although some studies have been made of waves of longer and shorter periods, and the waves are commonly termed microseisms.

There is a great abundance of literature on this subject and yet many aspects remain completely puzzling to seismologists. There exists a

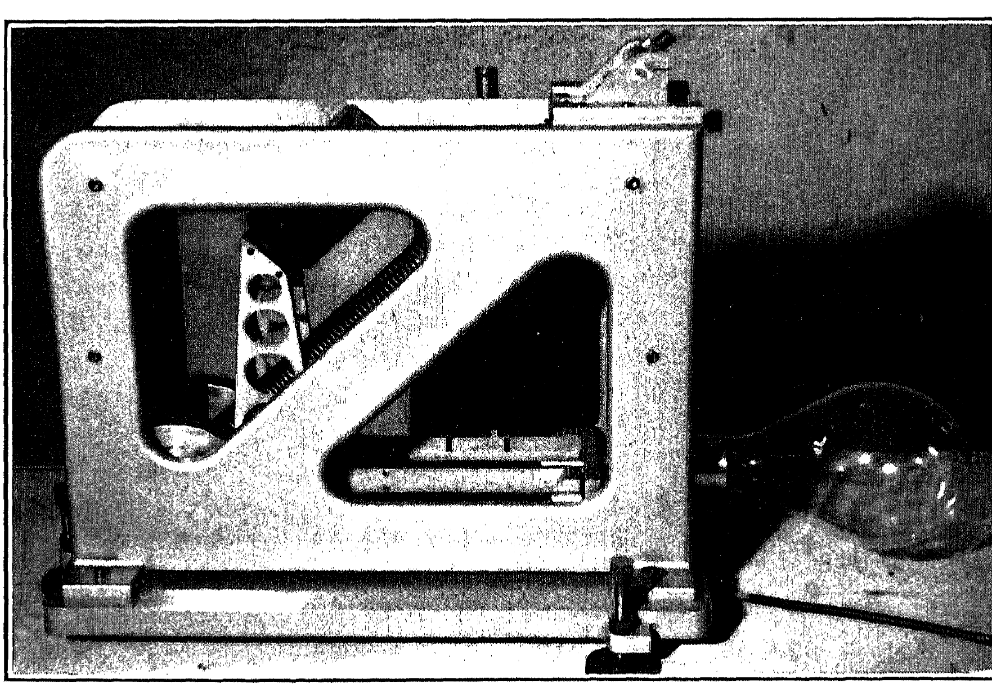

FIG. 3 — Sprengnether vertical-component seismometer

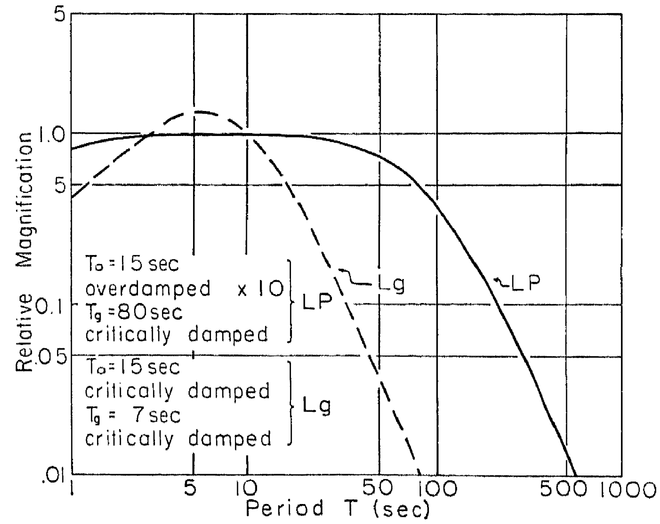

FIG. 4 — Theoretical seismograph magnification, normalized at ten seconds; response curves of LP and Lg instruments (courtesy George Sutton)

clear and unmistakable correlation between these waves and meteorological disturbances at sea; when suitable disturbances are present, the microseism level on the entire continent will maintain itself at high intensity in a manner generally correlatable with the storm. Controversy centers about the mechanism by which energy in the atmosphere is transferred to the ground beneath the seismograph station.

Many theories have been advanced to account for this phenomenon. The surf hypothesis, as the name indicates, calls on water waves breaking against the coast as a source of seismic energy. The *Longuet-Higgins* [1953] theory relies on constructively interfering trains of ocean swell to transmit pressure to the ocean bottom directly beneath. The theory of *Press* and *Ewing* [1953] explains the recorded periods as the result of normal-mode wave propagation along an ocean path. There are many others. None have been able to explain all the observed data satisfactorily. Perhaps this in itself is an indication that more than one mechanism is required for a satisfactory solution. Certainly, for example, a seismograph situated very near to an ocean beach must record the effect of the surf in some manner. To what extent an inland station feels the same effect, if at all, becomes a much more complex question.

It now appears that, although classical methods of microseism study, for example, correlation of microseism periods and amplitudes with waves, winds, storm position, etc., have been informative in the past, new approaches will be required for a complete solution of the microseism problem. One of them, already used in a few instances, is the study of propagation of earthquake surface waves of the same period. The use of an impulsive rather than a steady-state source permits the isolation of many aspects of the problem and a combination of the two methods cannot fail to be enlightening.

A second approach, related to the above, is that, whereas the normal tendency is to study microseisms at coastal stations where the level is high, a great deal might be learned if data from inland stations were included. It is known, for example, that great crustal discontinuities occur at continental margins and that earthquake waves are severely affected in these regions. Propagation along the continental margin departing from the great-circle path between epicenter and station is a distinct possibility and microseism data should be correspondingly complex. Hence the margin might be a poor location for a station for some aspects of microseism studies. It is known in the few studies available that at inland stations or at coastal stations where microseisms come from a distant body of water across a long segment of continental path, the microseisms, particularly with regard to particle motion, are less complex. Certainly, it would be an advantage to be able to understand these simpler cases before attempting to unravel the more complex data.

A third possibility which has not been exploited to a great extent concerns the use of three components of ground motion. If microseisms are the result of more than one phenomenon then there is the possibility that some component of motion might predominate in one situation and not in another. For example, for microseisms of longer periods, 10 to 20 seconds, definitely known to be caused by the surf or near-shore swell, the longitudinal horizontal component predominates. If the surf causes some portion of the shorter-period microseisms at a given station, then the relative amplitudes of the respective components, particularly those involving the vertical component, might be expected to vary as the type of microseism varies. This kind of study, of course, is only possible where good three-component instruments are available, not a common situation, but one which will be improved considerably during the IGY.

Application of the ocean-bottom seismometer, when it is available, to the microseism problem

also appears to be a fruitful approach to the problem and may ultimately prove to be the definitive one.

Conclusion—The above is a brief and cursory discussion of some selected topics of earthquake seismology. Enough evidence is presented, though, to give some indication of the large quantity of significant information on the Earth which this branch of science has produced in its relatively brief history. Certainly seismology has provided the bulk of our knowledge of the Earth's interior. That the science is currently in a productive stage is clearly attested by the quantity of papers of high calibre appearing in present-day literature. Speculation on the future reveals many frontiers which give every promise of revealing results at least as interesting and important as those of the past.

The new information to be found and the rate at which it will be forthcoming is clearly a function of the amount of effort which goes into the field. The seismological program of the IGY is wisely chosen to concentrate on important topics and the increased activity during the IGY should serve as a stimulus to the field in the near future. It is fitting that this should be the case since seismology is a science inherently international in character.

The relationship between seismology and other IGY disciplines is in many cases quite close. Geomagnetics, gravitational, and thermal studies rely heavily on Earth structures derived from seismology. Seismic methods are a valuable tool in oceanography and glaciology. In fact, when one is concerned with the physics of the Earth it is virtually impossible to treat one branch of geophysics apart from its interrelationship with other branches.

The position of the United States in seismology has long been a strong one, particularly since the increase in activity in this field following the San Francisco shock in 1906. Many of the leading seismologists of the world today live in the United States. There are, of course, many outstanding seismologists in other parts of the world and there has been pronounced acceleration of effort recently in this field in many countries. In recent years, the Soviet Union, in particular, has built a vast network of seismograph stations which in some respects is unequalled elsewhere. Such efforts are certain to produce worthwhile results.

In conclusion, the field of seismology is, at present, a productive one with promise of many new, interesting, and significant results in the future. It is particularly well suited to be a part of the IGY program.

References

Benioff, H., B. Gutenberg, and C. F. Richter, Progress report, Seismological Laboratory, Calif. Inst. Tech. 1953, *Trans. Amer. Geophys. Union,* **35**, 979–987, 1954.

Benioff, H., Seismic evidence for crustal structure and tectonic activity, *Crust of the Earth,* Geol. Soc. Amer. spec. pap. 62, 1955.

Bullen, K. E., An introduction to the theory of seismology, p. 119, *Cambridge Univ. Press,* 1953.

Bullen, K. E., *Seismology,* Methuen, 131 pp., 1954.

Bullen, K. E., Some trends in modern seismology, *Science Prog.,* **43**, 211–227, 1955.

Byerly, P., Nature of faulting as deduced from seismograms, *Crust of the Earth,* Geol. Soc. Amer. spec. pap. 62, 1955.

Ewing, M., and B. C. Heezen, Some problems of Antarctic submarine geology, *Geophys. Monogr. 1,* Amer. Geophys. Union, pp. 75–81, 1956.

Ewing, M., and F. Press, Structure of the Earth's crust, *Encycl. Phys.,* **48**, *Geophys. 1,* Springer Verlag, 1956.

Gane, P. G., A. R. Atkins, J. P. F. Sellschop, and P. Seligman, Crustal structure in the Transvaal, *Bul. Seis. Soc. Amer.,* **46**, 293–316, 1956.

Gutenberg, B., Low-velocity layers in the Earth's mantle, *Bul. Geol. Soc. Amer.,* **65**, 4, 337–348, 1954.

Gutenberg, B., and C. Richter, Seismicity of the Earth, *Princeton U. Press,* 1954.

Hodgson, J. H., Nature of faulting in large earthquakes, *Bul. Geol. Soc. Amer.,* **68**, 611–644, 1957.

Longuet-Higgins, M. S., Can sea waves cause microseisms, *Symposium on Microseisms,* Nat. Acad. Sci. — Nat. Res. Council Pub. 306, 74–93, 1953.

Press, F., Determination of crustal structure from phase velocity of Rayleigh waves, pt. I: Southern California, *Bul. Geol. Soc. Amer.,* **67**, 1647–1658, 1956.

Press, F., and Maurice Ewing, The ocean as an acoustic system, *Symposium on Microseisms,* Nat. Acad. Sci. — Nat. Res. Council Pub. 306, 109–113, 1953.

Ritsema, A. R., Earthquake-generating stress systems in southeast Asia, *Bul. Seis. Soc. Amer.,* **47**, 267–280, 1957.

Tatel, H. E., and M. A. Tuve, Seismic exploration of a continental crust, *Crust of the Earth,* Geol. Soc. Amer. spec. pap. 62, 1955.

Lamont Geological Observatory, Palisades, New York

Gravity Observations during the IGY

George P. Woollard

Introduction—The Earth's gravitational field is related primarily to its mass and rotation. If the Earth were a nonrotating sphere of homogeneous composition without surface irregularities there would be essentially a uniform gravitational field everywhere on its surface. However, the Earth is not homogeneous in composition, it is not a sphere, it does rotate, and there are marked surface mass irregularities related to the continents and ocean basins, mountains and valleys as well as changes in geology.

As a consequence of Earth rotation and polar flattening the acceleration of gravity varies approximately 5 cm/sec^2 (5 gals in gravitational force units) between the equator and the polar regions; enough to change the weight of a 200-lb man by one pound. At any given latitude the variations are not nearly as large but do get up to about 0.3 gal. These changes, while small considered in gross form, are quite large when it is considered that reliable measurements of small changes in gravity can be made to better than 0.0001 gal. Because of this facility with which changes in gravity can be measured, such measurements are useful for studying many factors related to the Earth. Some of these are the over-all shape of the Earth, the departures from the gross form (undulations of the geoid), errors in astronomic determinations of position related to warping of the gravitational potential surface (departure of the vertical), crustal structure, local geology, crustal strength and rigidity, thickness of the polar ice caps, ice movement, and prospecting for minerals and oil.

While the physical dimensions of the Earth can be fairly well approximated from astronomic observations, there is still sufficient uncertainty regarding its actual form that there is no unanimity among geodesists as to the exact mathematical equation that best describes it. If it were possible to carry out triangulation measurements over the entire Earth as in any one continent, the problem would soon be resolved, but inasmuch as about two-thirds of the surface of the Earth is covered by water this procedure is not possible. One approach to this problem of the Earth's shape is through measurements of the pull of gravity. Offhand this would appear to be a very simple operation. Just measure enough values of gravity, correct these for the outward centrifugal force related to the Earth's rotation and the effect of variations in surfical mass related to the elevations of the observation sites and the surrounding terrane, and the result should be a direct evaluation of the shape of the Earth. There are, however, certain other factors related to geologic consideration such as the density of the surface rocks and changes in crustal structure that must be considered as well as such practical considerations as the accuracy with which an observation is made, the location of the observation site and its elevation. Fortunately the relatively large gravitational effects related to mountain ranges and major geologic changes are compensated for by changes in crustal structure. That is, there is a situation which is analogous, if not identical, to that associated with a body floating in a viscous liquid. Any excess in surface mass, such as a mountain or an area of dense rocks, is underlaid by a 'root' in which lower density crustal material displaces a mass of denser subcrustal rock material so that hydrostatic equilibrium is approximated. Thus beneath a mountainous area there is a deep root (thick crust) and beneath oceans filled with low-density water a thin crust bringing denser subcrustal material nearer the surface. This results in equal pressure being achieved above about the -100 km level. This phenomenon, known as isostasy, gives effective cancellation of the mass effect of the surface topography and geology.

While there are exceptions where the surface mass irregularities are compensated for by crustal flexure similar to that observed for a man standing on a sheet of ice, indicating the crust has sufficient strength to carry local loading without local isostatic compensation, by and large, isostasy is closely approximated over most of the Earth. As a consequence of this phenomenon, only the elevation and position of the observation site is usually important in determining the average gravity value of an area for geodetic purposes. As these two factors can be reliably

determined on land and approximated sufficiently well at sea, the critical factor becomes the gravity observation value itself. It is paradoxical that, while small changes in gravity can be measured with high precision, large changes cannot. Since all of the world's gravity values are based upon relative measurements from a single point (Potsdam, Germany) or sub-bases directly tied to Potsdam, there is considerable uncertainty as to the accuracy of gravity values reported throughout the world. One of the objectives of the United States IGY gravity program is to check the accuracy of the national gravity bases and to develop a network of first order gravity reference bases that will serve both as control points for integrating the world's gravity data and as a standard for determining the accuracy of gravity measurements anywhere.

Earth measurements—To define the degree of polar flattening to a significant figure beyond the present approximation of 1/297 as well as define the departures of the actual earth shape from a simple mathematical form, such as is represented by a biaxial ellipsoid of revolution, an accuracy of 0.001 gal is required. That is, a change in gravitational attraction of one part in one million must be reliably measured over a range of 5 gals (the equator to the poles). While gravimetric instruments having a higher sensitivity have been developed for use in connection with the geologic exploration for oil and minerals, the accuracy of such instruments in measuring a change of 5 gals may not be better than 0.03 gal. This is because such instruments are essentially spring balances similar to the old-style butcher's scale. Gravity changes are measured in terms of the elongation of the spring for a given mass attraction. Actually, since it is difficult to measure small changes in spring length directly, the spring is connected through a suitable linkage to a screw with a dial head. In reading the instrument the mass attached to the spring is always brought to the same position by changing the tension in the spring. Gravity differences are thus determined in terms of spring tension as recorded by turns of the screw read from the dial. These dial values, however, are usually not linearly related to changes in gravity. Part of this non-linearity is related to the spring itself, part to errors in marking the dial divisions on the screw head, and part to non-uniformity in the pitch of the threads on the screw. With a weak spring requiring many turns to effect a given change in elongation the defects of the screw and dial are relatively unimportant and high sensitivity can be obtained. Such an instrument, however, has a very limited range. In order to obtain a high range as with a geodetic-type meter, sensitivity must be sacrificed and a stiffer spring used. With this type instrument the defects in the screw and dial become perhaps even more significant than the linear response of the spring. Because of difficulty in manufacturing to the exacting tolerances required, each instrument of this type, even when built to the same specifications, behaves somewhat differently. The principal problem therefore in using this type of instrument, called a gravimeter, is in getting an adequate calibration. There are two ways of doing this. Both involve determining the gravitational acceleration at a series of sites covering a large change in gravity. One is based on the determination of absolute gravity from the period of an oscillating pendulum or the acceleration of a falling body. The other method is to measure the differences in gravitational attraction between a series of sites in terms of the difference in period observed for an oscillating pendulum.

Standardization measurements—The mechanical difficulties of measuring both time and length to the required order of accuracy for absolute gravity measurements, limits as yet the utilization of this type of measurement for calibration purposes. With relative pendulum measurements only time must be measured to determine differences in gravity, and with modern timing devices it is possible to measure changes in gravity using this method to better than one part in one million. However, the success of the measurement depends upon the length of pendulum as well as the environment of measurement staying constant. If the environment changes in any way whether temperature, pressure, magnetic field, or viscosity of medium, its effect on the pendulum period must be accurately known, otherwise the measurement will be of little significance for establishing a calibration standard. At present there appear to be only two or three sets of pendulum apparatus having the required precision for establishing a series of gravity standardization measurements. One is the Invar compound pendulums of Cambridge University, England. Another is the quartz compound

pendulums developed by the Gulf Research and Development Company in the United States, and a third, as yet only partially tested, is the pendulum apparatus recently developed by the Dominion Observatory in Canada.

Although the Gulf and Cambridge pendulums are similar in that they are compound systems utilizing two pendulums swinging 180° out of phase with each other in order to cancel out the effects of induced sway in the support, in other respects they are different. The Gulf apparatus uses only two pendulums made of quartz which swing in a sealed case which is never opened. Observations are made at a constant temperature and pressure and the period is measured and recorded directly with a Berkeley counter. The Cambridge apparatus utilizes two different sets of Invar pendulums which are swung in various combinations. The case therefore must be opened to make substitutions, and while the same pressure is usually used for all runs, no attempt is made to operate at a constant temperature or viscosity. Observations are recorded photographically and the period data are picked off from these records. Both units use crystal driven synchronous motor chronometers for determining the pendulum period and are regulated by zero beating against the carrier frequency of WWV time signals. Both have peculiar problems. With the Gulf pendulum the case must be ionized with a radioactive salt to get rid of electrostatic charges developed on the quartz. With the Cambridge pendulums the instrument must be oriented with respect to the Earth's magnetic field and observations made in a constant magnetic field through the use of a Helmholtz coil.

It is therefore significant despite these differences that the results obtained with the two sets of equipment are nearly identical. Comparative measurements made over about eight-tenths of the total change in gravity with these two sets of instruments show that they give an average agreement to about three to five parts in ten million (0.0003 to 0.0005 gal).

Since a pendulum observation requires approximately two days and involves about 700 lb of equipment, whereas a spring-type gravity apparatus requires no more than ten to fifteen minutes for an observation and may weigh as little as five pounds, it is obviously advantageous to use a spring-type instrument for making any extended series of measurements. However, as indicated above, in order for gravimeter measurements to be significant, the characteristics of such an instrument must be determined by intercomparisons of values as determined at reliable pendulum observation points over a sufficient change in gravity to cover the operational range of the gravimeter. This has not been possible up until the last two or three years because there did not exist the requisite series of first order pendulum observations.

Under the auspices of the Cambridge Research Center of the U. S. Air Force, a series of such measurements has been established between Alaska and Mexico and between Norway and South Africa by the University of Wisconsin using the Gulf pendulums. Under the IGY program these measurements are being extended so that there will be five series of meridional measurements covering the Earth: Alaska to Cape Horn via the west coast of North and South America, Alaska to Antarctica via Japan and Australia, Greenland to Cape Horn via the east coasts of North America and South America, and Norway to South Africa with measurements down both the east and west coast of Africa. It is hoped to have both Gulf and Cambridge pendulum measurements made at the same sites throughout the world although as yet provision has not been made for a complete program of measurements with the Cambridge pendulums.

As the pendulum measurements are strictly for over-all control purposes, the measurement sites are being spaced about 300 to 500 mi apart, the exact spacing depending upon the gravity interval. As the time factor is important in gravimeter measurements because of instrument reading changes with time known as 'drift,' the pendulum observations are being made only at places served by commercial air lines. Where the pendulum observation site is not at the airport, auxiliary sub-bases are being established at the airport through the use of gravimeters. In this way it will be possible to make calibration measurements for a high-range geodetic type gravimeter on a continuing flight during the 10- to 20-minute period that the plane is on the ground.

World network of gravity bases—Another phase of the IGY gravity program is the development of a world network of gravity bases using high-range gravimeters. This is a con-

tinuation of a program started originally under the auspices of the Office of Naval Research at the Woods Hole Oceanographic Institution. As many of the measurements originally made under this study were completed before a satisfactory calibration standard had been established, it will be necessary to recalculate these earlier results as well as take check readings at key points to satisfactorily adjust these measurements to conform to the present pendulum standard. It is these measurements which will be most valuable in evaluating the accuracy of existing gravity measurements throughout the world and in establishing the accuracy of the national gravity base values.

Marine gravity program—A third phase of the IGY gravity program is that of gravity observations at sea. Prior to this year these measurements, because of the instability of the ocean surface, had to be made either on bottom in shallow water or in a submarine in deep water. Through the development of the new Graf marine gravimeter and the use of a gyro-stabilized platform it is now possible to carry out surface-vessel gravity measurements. Tests are now being conducted to determine the comparative accuracy of these measurements with earlier ones taken with pendulum apparatus in a submerged submarine. The effect of the motion of the vessel is a prime factor in influencing the accuracy of such measurement and sea state thus becomes a critical factor. With a high sea a submarine may still be the only way of making observations. While it is too soon to gage the accuracy of these new gravimeter measurements under all conditions, comparisons made using both pendulum apparatus and other newly developed marine gravimeters in a submarine suggest that under good conditions (a calm sea) an accuracy of about one to two milligals (0.001 to 0.002 gal) is obtained. With a rough sea even the submarine pendulum observations may have an accuracy of no more than about 4 mgal. For analysis purposes an even greater limitation on gravity measurements at sea is the problem of location when beyond the range of LORAN, and navigation must be based upon dead reckoning because of poor sky visibility. However, despite these limitations the IGY gravity program at sea will be invaluable since there are so few observations and as so much of the Earth's surface is covered by the oceans.

The Lamont Geological Observatory of Columbia University has the primary responsibility for the United States IGY gravity program at sea and is using both pendulum equipment developed by Vening Meinesz of Holland for use on submarines and the newly developed surface-vessel Graf gravimeter. In addition the U. S. Navy Hydrographic Office is also making observations using a gravimeter developed by the LaCoste-Romberg Co. of Austin, Texas for use on submarines. These measurements in conjunction with the land gravity program should do much to resolve the problem of the shape of the Earth, the undulations of the geoid as well as give valuable data concerning crustal structure and geology.

Polar measurements—Another phase of the gravity program is that of observations made using gravimeters on two ice floes in the Arctic Ocean, one off Greenland on the ice island T-3 (Fletcher's Ice Island) and the other off Alaska on a new floe station known as Station A. As these two ice floes drift across the Arctic Ocean a series of observations is being built up giving much needed information on gravity variations in the north polar region. These observations will also give oceanographic information since the values recorded will also be affected by the daily tidal variation in the height of sea level. To maintain control on these measurements so that they will have maximum value, a series of gravity connections to each station is being made from the resupply points, Fairbanks, Alaska, and Thule, Greenland, where gravity bases have been established. These tie measurements, which are being made with a high-range geodetic meter, will serve to establish the drift rate for the ice-floe instruments and to give a series of check values covering the course followed by the ice floes.

An additional phase of the United States IGY polar gravity program is the use of gravity measurements in studying the thickness of the ice in Antarctica. Each of the traverse parties operating out of the Marie Byrd, Ellsworth, and Little America stations in Antarctica, in addition to making seismic determinations of the thickness of the ice are also making gravity measurements. By having some seismic values on depth of ice to serve as a basis for analysis, it will be possible to use the gravity variations to evaluate changes in the thickness of the ice.

This is analogous to the use made of gravity in oil prospecting. In addition to this use of the Antarctica measurements, the values of course will also give information having both geodetic and general geophysical value.

On a long-term program the gravity observations in Antarctica can also be used to determine possible wasting or accretion of the ice cap. For example, repeat observations over a series of years at sites such as the South Pole should give reliable information on this problem.

Earth-tide studies—Another phase of the IGY gravity program is the study of the response of the Earth's crust to the tidal attraction of the Sun and Moon. Measurements using supersensitive gravimeters capable of recording variations of one part in one billion of the Earth's field are being made for a period of 31 days at each of a series of selected sites chosen because of their geological setting. It is hoped these measurements will give pertinent data concerning crustal strength and rigidity. The United States' Earth-tide program, which is being carried out by the Institute of Geophysics of the University of California at Los Angeles, is integrated with that of other countries throughout the world so that simultaneous observations will be made on a global basis. In this way all results can be related in terms of both time and degree of response as well as geologic setting.

Other gravity studies—While the above constitutes activity that is being officially carried out under the United States IGY program, unofficially the program is being aided by various oil and geophysical exploration companies. Several organizations, for example, are making a conscious effort to tie their local exploration gravity surveys throughout the world to the world gravimeter and pendulum network. This applies to both old and new surveys. As it is planned to make results from many of these surveys immediately available and results of other surveys available later, this will constitute a notable contribution to the over-all gravity program.

In connection with this unofficial phase of the IGY program, the aid of the Special IGY Committee of the Society of Exploration Geophysicists and the Special Committee for the Geophysical and Geological Study of the Continents of the American Geophysical Union in securing the above cooperation cannot be overemphasized.

Department of Geology, University of Wisconsin, Madison 6, Wisconsin

The US-IGY Program in the Antarctic

LAURENCE M. GOULD

Introduction—Looking over our shoulders as we assemble to open the Antarctic phase of the International Geophysical Year are those great explorers and scientists of many countries who pioneered in the study of Antarctica. Cook, Bellinghausen, Wilkes, and Ross each made their distinctive contributions a century or more ago. Although for the following 50 years no further Antarctic exploration was carried out, in 1861, not far from the National Academy of Sciences, Commander Matthew Fontaine Maury of the U. S. Navy proposed an internationally coordinated effort in the scientific exploration of the Antarctic.

This plea lay dormant until 1904 when Henryk Arctowski revived it at the Eighth International Geographic Congress, held in Washington, D. C. The recommendations passed at a preceding session of this same Congress in Berlin in 1899 induced a cluster of individual expeditions that lasted into the second decade of this century. Some of the greatest names in all exploration belong to this period: Nordensskjold, Scott, Shackleton, Amundsen, and Mawson. Then came the air age with flights by Wilkins and Byrd in 1928 and 1929. Admiral Byrd was the first American to lead an expedition to Antarctica since Wilkes, 90 years earlier. To him goes credit for having focused attention on Antarctica through his four succeeding expeditions.

Now the nations of the world are engaged in a new kind of investigation with the emphasis shifted from geographical to geophysical and from individually inspired expeditions to broad, coordinated scientific undertakings, such as was proposed by Maury nearly a century ago. Twelve nations will have established 65 scientific stations in Antarctic and sub-Antarctic locations during the International Geophysical Year.

Establishment of Antarctic stations—In March 1953 the United States National Committee for the International Geophysical Year was established by the National Academy of Sciences to prepare and carry out participation of American scientists in this international program. Today, after four years of preparation, we are present to witness the commencement of this program at six stations in the Antarctic, one of which is jointly operated with New Zealand, and at the many other stations of other countries.

Great logistic difficulties have been faced and overcome in the Antarctic. In our program the United States Navy was assigned, by the Department of Defense and at our request, the task of establishing and maintaining facilities necessary for the completion of the USNC-IGY scientific program in this region. In order to assure scientific observations during the period of the IGY, it was necessary to begin operations several years ago. In the fall of 1954 the icebreaker U.S.S. *Atka* departed for the Antarctic on the initial reconnaissance for the USNC-IGY Antarctic Program, exploring the Ross Sea and eastward along two-thirds of the Antarctic coastline for possible sites for future stations.

Information obtained during this and previous voyages served as a basis for Operation DEEP FREEZE I in which ships of U. S. Navy Task Force 43, under the able direction of Rear Admiral George Dufek, departed for the Antarctic late in 1955 and during which Little America IGY Station was constructed at Kainan Bay in the Ross Sea, thirty miles from the sites of Admiral R. E. Byrd's earlier Little America stations. While this first USNC-IGY Antarctic station was being constructed, units of the Task Force were engaged in constructing an air facility at Ross Island in McMurdo Sound. From the ice runway which was prepared on the bay ice it was planned to air-deliver the material and supplies, scientific equipment, and men for the Amundsen-Scott IGY South Pole Station, and to support the overland tractor operation which was needed to construct the Byrd IGY Station on the Rockefeller Plateau in the interior of Marie Byrd Land.

Occupied during the austral winter with the completion of these facilities, the wintering-over parties at both stations were relieved during Operation DEEP FREEZE II, 1956–57. Little America Station was fitted out for the commencement of its scientific program. Following the initial landing at the South Pole by Admiral Dufek, in the middle of October, 1956, units of

the 18th Air Force, which flew to McMurdo Sound via New Zealand, began the air delivery of material and equipment for the construction of the USNC-IGY station at the South Pole. From Little America, a tractor train, led by experienced U. S. Army personnel, completed the reconnaissance of the heavily crevassed area of the approach to the Rockefeller Plateau, and prepared a safe route to the interior of Marie Byrd Land. Following this trail, two other cargo trains with air support delivered equipment and supplies for the Byrd IGY Station.

During this period, other units of Task Force 43 landed construction personnel at Cape Hallett where the joint New Zealand-United States Hallett IGY Station was constructed. This Task Group then proceeded to the Windmill Islands on the Knox Coast and built the Wilkes IGY Station before proceeding on their return voyage to the United States. A third unit of Task Force 43 completed the deepest penetration yet made into the Weddell Sea in search of a site for the Ellsworth IGY Station. After an arduous voyage, during which both ships of the Task Force battled their way through heavy ice, a site was finally located at the western end of the Weddell Sea, and the Ellsworth Station constructed during February 1957.

By March 1, 1957, the operational aspect of Operation DEEP FREEZE II had come to an end. Ships of the Task Force were on their return voyage to the United States, and U. S. Navy and Air Force planes had returned to New Zealand from the Naval Air Facility at McMurdo Sound. The IGY scientific personnel and equipment had reached their assigned stations and the facilities necessary to support this program were being completed.

During early March, under the leadership of the Wilkes Station glaciology personnel, a small satellite station was constructed on the ice cap some 50 mi southeast of the station. The one-building station, which was established in 14 hours, has been periodically utilized in the past few months. Significant glaciological and meteorological observations have been undertaken.

Further exploration from Wilkes Station has included a six-day trip to the Vanderford Glacier, during which a system of movement stakes were established. It is planned to resurvey this system in six months.

Scientific objectives—Why are we interested in the Antarctic from a geophysical point-of-view? First, it is a rather large part of our planet, some six million square miles in area, and a largely unknown part, too. Second, it is the largest repository of ice in the world, containing 86 pct of all the world's glacial ice. Third, it is the world's most efficient cold-air factory, far more so than the Arctic. It also contains the Pole or the hub of the atmospheric circulation in the southern hemisphere. Fourth, its melting ice creates vast amounts of cold water, which sink to the bottom of the ocean and, as the Antarctic Bottom Current moves across the equator, moves into the northern hemisphere. Fifth, it enables study to be made of the aurora australis and comparisons with the aurora borealis. Sixth, it contains the South Magnetic Pole and affords the opportunity for extensive geomagnetic studies. Seventh, it presents a stable platform for the study of the thermal and electrical properties of an atmosphere cut off from sunlight for many months. Ionospheric phenomena affecting radio propagation will be of particular concern as will the study of the concentrations of cosmic radiation.

Some scientific results—Even now, before the official start of the International Geophysical Year, significant new scientific discoveries have been made by the men who assumed their Antarctic posts 6 to 18 months ago to wait the coming of July 1, 1957.

As expected, the most fascinating discoveries have come from those stations which, for the first time in history, were established deep in the interior of Antarctica. A new world's record low temperature was confidently predicted at the geographic South Pole (elevation 9200 ft) but not under the interesting circumstances that it occurred. Following the relatively warm summer temperatures, hovering between 0° and −20°F in December and January, the temperature fell precipitously to −67°F on February 28, to −81°F on March 24, and to the new world's record of −100.4°F on May 11, much lower than the previous value of −90°F observed in northeast Siberia many years years ago and −94°F observed at the inland Soviet IGY station Komsomolskaya a few months ago. The astonishing feature of the low temperatures at the South Pole is that they are accompanied by fairly brisk wind speeds of 10 to 15 mi/hr in marked contrast to

calm conditions accompanying previous extreme low temperatures.

Although above the surface the air temperature increases greatly with height (as much as 58°F in the lowest thousand feet) this has little effect in raising the surface temperature unless the wind exceeds 18 or 20 mi/hr or clouds move in. In the first case heat is transported downward by turbulence, and in the second case by infrared radiation from the warmer clouds. It was mainly by this latter process that within three hours after the record low of −100.4°F was observed the surface temperature rose rapidly to −82°F.

At the same time that the Amundsen-Scott IGY Station observed −100°F temperatures, the Little America Station 800 mi to the north enjoyed summer temperatures of +30°F in the face of a 60 mi/hr gale from the ocean.

The second U. S. interior station, the Byrd Station (80° S, 120° W) also reported an interruption in the normal seasonal decline in temperatures: April and May averaged exactly the same, −32.4°F, but with the minimum temperature for May nearly 1°F warmer than that for April.

In the measurement of ice thickness in the neighborhood of the Byrd Station another unexpected result emerged. IGY scientists at this station, which is 5000 ft above sea-level, reported thickness of the underlying ice to be 10,000 ft which means that 5000 ft of ice must extend below sea-level! These measurements were made subsequent to the completion of an important scientific achievement during January 1957: the glaciology-seismology oversnow traverse along the 647-mile trail over the Ross Ice Shelf from Little America and up to and across the Rockefeller Plateau to the Byrd Station. A seismic profile was carried out during this trip, and it was discovered that ice depth of the Plateau varied from 2000 to 8000 ft during the course of the traverse, increasing toward the Byrd Station. Although there have been sufficient observations in the vicinity of the Byrd Station and over a distance of six miles to the northwest to substantiate this reported ice thickness, we must wait for complete confirmation until after October of this year. At that time extensive measurements of ice thickness and supplementary gravity and seismological observations will be carried out over much of Marie Byrd Land during further traverses. Then it will be possible to see whether such sub-sea-level ice deposits occur in narrow fjord-like valleys, such as are found under the Greenland Icecap and in Queen Maud Land (Antarctica), or whether they denote the presence of a vast frozen sea in what is called West Antarctica.

Our ideas about the underlying terrain in East Antarctica also may have to undergo change if an observation of ice thickness made in the vicinity of the Soviet IGY Station Pioneerskaya (250 mi inland) turns out to be representative of large areas. This station, which is at an elevation of 9000 ft, rests on ice from 10,000 to nearly 12,000 ft thick.

These preliminary values of ice thickness indicate strongly that there is much more ice in Antarctica than was previously believed.

No one knows whether the great Antarctic Ice Sheet is increasing or decreasing in mass. At one time, as indicated by geological evidence, it was 1000 ft thicker than at present. During the International Geophysical Year a set of bench-marks will be established against which future measurement of ice levels can be compared. But this is a slow process and it is possible, given sufficient meteorological and oceanographic measurements, to arrive at an answer earlier. If we can measure the annual accumulation of snow, either directly at a large number of stations or indirectly by measuring the amount of water brought in from the oceans by the winds, the import of ice can be determined.

To measure the export of ice we must know how much snow is blown seaward by the winds, how much ice is broken off from the great Antarctic ice shelves, and how much ice is melted by the oceans. Some very approximate figures obtained from various sources would indicate that perhaps today there is an approximate equalization of import and export, but we must have much more extensive and detailed observations before conclusions can be reached about the Antarctic ice budget.

In anticipation of the commencement of the International Geophysical Year, the Antarctic Weather Central, for which the United States has accepted the international responsibility, has already begun at Little America four daily weather broadcasts simultaneously on three radio frequencies. These broadcasts include twice-daily upper-air chart analysis. The daily weather

broadcasts include surface synoptic reports and upper-air data received through the IGY mother-daughter communications network covering 65 stations in the Antarctic region and from standard international meteorological broadcasts. These weather broadcasts are made on a predetermined schedule for reception by all Antarctic stations and are re-broadcast by the USSR Mirny Station to ensure adequate coverage in the African quadrant of the Antarctic Coast. The analysis program includes twice-daily preparation of upper-air charts, four sea-level charts, thickness maps, and time cross-section charts for nine Antarctic stations. These analyses are included in the daily weather broadcast.

Accomplishments have also been reported in the other scientific disciplines to be studied at the Antarctic stations. All-sky cameras to photograph the aurora australis have been successfully installed and tested at each USNC-IGY station; additional auroral equipment, including a scanning spectrometer at Little America Station, has also been put into operation. Auroral data are being radioed back to this country for analysis and study despite the difficulties encountered due to electronic problems and extremely cold temperatures.

Equally important is the successful installation of the highly complex ionospheric recording equipment, installed at each of the USNC-IGY Antarctic stations. From the regular data that this equipment has already made available, it is hoped an explanation will come to some of of the physical peculiarities of the upper atmosphere which so drastically affect radio communications and which may relate to the other phenomena under study. Adding to the overall picture of the upper atmosphere are the cosmic-ray instrumentation now in operation at the Wilkes IGY Station and the geomagnetic recorders at all stations but Ellsworth.

Seismic instruments have been installed at five stations. At the South Pole the equipment is mounted on a special platform at the end of a 1000-ft snow tunnel which was completed in April by the 18 men wintering at the station. It is expected that this net of seismographs will materially aid in providing a southern control for earthquakes in the southern hemisphere. These observations will make possible a much more accurate delineation of the seismic belts of the far south.

Although we now have only preliminary data available from these disciplines, the instruments in each discipline are operational and have withstood a period of extensive tests. We anticipate that the data we are getting and shall obtain, will lead to further understanding of physical phenomena.

There is one feature of the present IGY, as compared with its limited, North-Polar predecessors of 1882–83 and 1932–33, that has become a reality: the realization that practically all the geophysical sciences are interrelated. The location of the South Magnetic Pole in Antarctica permits less energetic cosmic-ray primaries to penetrate deep into the atmosphere. But also the belt of unusually low barometric pressure found at the coast means there is three to five per cent less atmospheric mass than elsewhere; this, combined with the low temperature of the air column above, so contracts the atmosphere vertically that various secondary radiations emanating from collisions of cosmic-ray primaries with air molecules can reach the Earth's surface in greater intensity. The height of the 100-mb surface at Maudheim in winter is 2000 ft less than at Thule and 5000 ft less than at Washington.

A second example is the inter-relation of meteorology, seismology, glaciology, geology, and botany in determining whether the inland ice is receding or growing, and in establishing a record of past variations in climate.

A third example is a solar disturbance, two of which occurred in early 1956. The first, on February 23, 1956, resulted in a great increase in cosmic-ray intensity, but with no immediate magnetic effects, while the second, on April 26, 1956, affected the ionosphere, causing an historic magnetic storm, radio-blackouts, aurora, and probably an increase in cosmic-ray intensity. The controversial question as to whether solar disturbances can cause significant changes in sea-level meteorology will probably be resolved by the more numerous and unusual observations collected during the IGY.

Carleton College, Northfield, Minnesota

The United States IGY Arctic Program

John C. Reed

Introduction—This paper describes the United States IGY Arctic program and, more specifically, the program that is being carried out on the Arctic Ocean. First, just a little background for orientation. The IGY is concerned with the whole Earth and with the geophysical phenomena that are related to it as a means of finding out more about this planet on which we live.

In this great international effort and in view of some of the basic facts of terrestrial geophysics, much of our interest is centered on the polar areas. The IGY and especially the United States and the Union of Soviet Socialist Republics, along with a number of other nations, are much involved in learning more about the north polar regions, the Arctic.

There are, of course, vast differences between the IGY programs in the Arctic and in the Antarctic. The Antarctic is a vast and high continent, surrounded by great oceans. The Arctic conversely is largely a major ocean basin surrounded by continents. Furthermore, those continents, embracing as they do the north temperate zone and most of the world's population centers, result in an urgent need for comprehensive information on the geophysical aspects of the Arctic for immediate and future practical application to many pressing problems of the human race. These problems involve transportation, communication, and natural resources and economics.

By tradition also the IGY effort is deeply concerned with the Arctic. The present IGY is the lineal descendent of the First and the Second Polar Years that were involved primarily with the Arctic. The First Polar Year was in 1882 and 1883 and then, as now, Pt. Barrow, Alaska, was one of the centers of the work. The Second Polar Year, 1932 and 1933, included auroral studies, ionospheric physics, glaciology, ice studies, and northern hemisphere weather charts.

The IGY organization includes an Arctic Committee to promote and attain coordination among the programs of the various scientific disciplines that are carrying on work in the North. In addition to the coordinating function, the Committee has an active responsibility in regard to the logistic support that generously is being supplied by the Department of Defense, largely by the Air Force.

The logistic problem in the Arctic is far different, and, in general, not as complex as in the Antarctic. No large continuing task-force support is needed as in the case of the Antarctic. Nevertheless, the problem is very substantial and the U. S. Air Force and other services have met the challenge magnificently. The story of the final selection of the site of one of the two U. S. drifting stations on the polar ice and the subsequent establishment of that station constitute a real epic of the Arctic.

The US-IGY effort in the Arctic is being carried out in Greenland, Canada, Alaska, and the Arctic Ocean over approximately 150° of longitude. Altogether there are about 50 stations, although some are only minor observation points. All but two or three of the IGY disciplines are represented in the Arctic program.

The remainder of this paper is limited to the two U. S. drifting stations on the arctic ice. One of these stations, Drifting Station A, is on sea ice now about 700 miles north of Point Barrow. The other is on Fletcher's Ice Island (Drifting Station B) now about 300 miles west of Ellesmere Island.

At Drifting Station A, work is underway in: aurora and airglow, geomagnetism, glaciology, seismology and gravity, meteorology, and oceanography. On Fletcher's Ice Island, work is being done in: glaciology, seismology and gravity, aurora, ionospheric physics, meteorology, and oceanography. In addition arrangements are underway to obtain repetitive aerial photography of as much as possible of the ice in the Western Arctic Ocean as a means of learning about the distribution and change of the ice cover of the sea. It is hoped that eventually similar photographs can be obtained from the USSR so that, taken together, a reasonable amount of information will become available about the sea ice.

Establishment of Arctic Basin Stations

Drifting Station A—In early March of 1957 an air reconnaissance was conducted by the Alaskan Air Command in order to locate a suitable site in the vicinity of 75° N, 155° W, for a planned USNC-IGY ice-floe station. On March 10, 1957, Joseph O. Fletcher, then Arctic Basin Projects Leader for the USNC-IGY, traveled to Alaska to aid in this reconnaissance. It was discovered that the ice conditions in the desired region were unsuitable for the establishment of the station because of an excessive amount of open water caused by an unusually warm winter in the western section of the Arctic Basin. For that reason the search was continued farther north and west and on March 30, 1957, the first landing was made on an ice floe; however, it was later decided that that floe was unsuitable. On April 12, 1957, a subsequent landing was made on another ice floe at about 80° N, 159° W. Five men and one tent were left, along with a radar reflector and minimum supplies in order to begin the work necessary for the construction of the station. The station is drifting in a generally north direction at about two miles per day.

While the reconnaissance was being carried out, arrangements were being coordinated in Washington by the USNC and the U. S. Air Force for the shipment of scientific cargo to Alaska. Project leaders were notified regarding shipping instructions, and the shipment of scientific cargo for Station A began about April 10, 1957. A representative of the USNC went to Ladd Air Force Base in order to coordinate IGY cargo shipments and program plans with the Air Force.

On April 23, 1957, a small tractor was dropped along with a weasel (oversnow vehicle) and a Jamesway hut. By April 25, thirteen men were working at the site on the ice floe and a paradrop of supplies and fuel was made.

On May 6 the scientific team began to arrive at Ladd Air Force Base and by May 9 all personnel were present. By that time several Jamesway huts had been erected and seventeen men were at the site. About 3500 ft of runway, 150 ft wide, had been completed.

The major airlift to the drifting station was made between May 20 and May 25, 1957. The first C-124 aircraft landed successfully on May 21, after the completion of the 5000-ft runway. From that date five flights daily were made until all cargo had been landed. Ten scientists and about the same number of support personnel will be at Station A during its period of occupation. The total facility includes about 20 Jamesway huts.

Station A is on a large ice floe which is several years old. The floe averages approximately nine feet in thickness. For maximum safety, the floe was chosen because it is surrounded by smaller broken fragments of sea ice; the fragments will protect the large floe from strains and pressures which might result from contact with other large floes. During the summer months the surface of the floe was partially covered with melt-water ponds, while during the winter several feet of drifting snow cover the ice. It is expected that the floe will drift in a northerly direction tending towards the east in the course of a two-year period. As the greatest hazard at an ice floe station is the breaking up of the floe because of pressure from neighboring floes caused by the interaction of ocean currents and wind, emergency procedures have been established to insure the safety of station personnel and equipment.

Fletcher's Ice Island Station (Drifting Station B)—Fletcher's Ice Island is a large tabular piece of very thick ice drifting in the Arctic Ocean. Its dimensions are roughly 9 miles in length, 4½ miles in width, and 140 to 160 ft thick. The origin of the ice island is probably the shelf ice of the north coast of Ellesmere Island. The ice island has been under surveillance since its discovery in 1950 and the general direction of its travels is clockwise in the area between the Pole and the Canadian Archipelago. It is not pack ice, being more massive, and can be considered permanent.

The island surface is generally above surrounding pack ice by about 20 ft and from the air presents a corrugated appearance. This is because of parallel ridges and troughs of ice, the cause of which has not yet been accurately determined.

The ice island is located favorably for the staging and air delivery of construction material, scientific equipment and personnel from Thule Air Force Base, Greenland.

On February 13, 1957, Fletcher's Ice Island was relocated on a reconnaissance flight, some 650 miles from Thule Air Force Base at about 82° 50′ N, 99° W. The first landing was made

on March 7, 1957. On April 5 construction of a 5000-ft runway was begun. Arrangements were made for an airlift of two years' supplies. Six C-124's were assigned to the task after completion of the runway. At that time temperature ranged from $-9°$ to $-40°$ F. William Knutson, the Air Force Station Commander, Norman Goldstein, IGY Station Scientific Leader for the initial phase, and several support personnel were on the ice island. By April 9, 1957, 2100 ft of runway had been cleared and it was felt that it would be completed by April 25. During that period, communications were infrequent because of intermittent blackout conditions.

On April 22, a ski-equipped aircraft landed, carrying a 4000-pound roller for the runway. Also, a paradrop of supplies was made by a C-54. On April 23, a C-124 of the Tactical Air Command with Robert W. Gates, Commander Task Force T-3 aboard, made the first wheeled landing after the runway had been completed. On April 24, a heavily loaded TAC C-124 sheared its nose gear while making the second wheeled landing. No personal injuries were sustained, but both inboard propellers were crushed and considerable damage caused to the fuselage of the aircraft.

Scientific personnel and cargo were arriving at Thule during the period. Operation delays were caused by problems in runway construction, but by May 18, airlift of a two-year stock of equipment and supplies was virtually completed to the station. All serious problems seem to have been overcome and in general everything seems to be going well. At the station, living and working facilities are in house trailers.

Administration—Responsibility for the establishment, maintenance, and conduct of both stations has been delegated by the USAF to a major Air Command (the Alaskan Air Command for Station A and the Strategic Air Command for Fletcher's Ice Island Station). The primary representative of each Command at the drifting stations is the Station Commander, an Air Force officer, who is responsible for the maintenance of the station as a whole and the safety of all personnel.

Responsibility for the execution of the IGY scientific program at each drifting station is delegated to a USNC-IGY Station Scientific Leader. The Station Scientific Leader is responsible for the supervision of the over-all scientific program at his station and for the coordination of scientific duties of all personnel at the station. The Station Scientific Leader advises and cooperates with the USAF Station Commander to resolve problems of joint concern.

Scientific Programs

Station A—The aurora and airglow program on Station A includes the use of two instruments operated by personnel from the Lamont Geological Observatory under contract with the Geophysics Research Directorate of the Air Force Cambridge Research Center. The first of these instruments is an all-sky camera, which takes a picture of the sky hemisphere every five minutes. The second instrument is a patrol spectrograph, which is an automatic instrument which has its entrance slit aligned with magnetic north, and takes spectrograms at a variable rate depending on the intensity of the light in the sky. Like the camera the instrument is intended for night use.

The geomagnetism program includes the use of an instrument supplied by the U. S. Coast and Geodetic Survey and operated by personnel from the Lamont Geological Observatory. The instrument is an Askania Variograph which operates continuously. In addition the instrument can be used to make absolute determinations of declination. The accuracy of the determinations is limited by the accuracy of determining a geographical azimuth by celestial means.

The purpose of the heat-budget project is to determine quantitatively the individual components of heat exchange at the ice-atmosphere interface and ice-ocean interface; and to relate the heat exchange between the ice pack and its atmospheric and oceanic environments to seasonal variations in thickness and the thermal regimen of the ice pack. Aside from its importance to determining the physical relationships which lead to the formation and maintenance of the ice pack, the heat-exchange studies being investigated under the project form a very basic and integral part of the determinations of the heat budget of the Arctic Ocean, and of the modification of air masses moving over the Arctic Basin. The program is being carried out through the Department of Meteorology and Climatology of the University of Washington.

The purpose of the sea-ice physics program is to determine the physical properties of sea ice and, in coordinated study with the heat-budget program, to relate those properties of the sea ice to the exchange of mass and energy between the ice and its meteorological and oceanographic environment. Specific studies include structure, air content, density, salinity, composition of salts, latent heat of melting, heat capacity, thermal conductivity, strength, problems of pressure ridges, crystallography, and morphology and thickness of the ice.

The meteorology program can be broken down into three main categories: surface synoptic, upper air, radiosonde observations, and specialized programs for study of radiation, carbon dioxide, precipitation chemistry, airborne radioactivity, and snow crystals.

The oceanography program of the Woods Hole Oceanographic Institution on Station A consists of the following: (1) hydrographic stations that use Nansen bottles and reversing thermometers in order to obtain a vertical profile to the bottom of temperature, salinity, and oxygen content, (2) measurements of ambient noise level in the Arctic Basin as part of an underwater sound program, (3) measurements with a bottom temperature probe of the temperature gradient in the ocean-bottom sediments. This latter measurement is part of the program being conducted at Harvard University to determine the heat flow of the Earth. The temperature gradient coupled with conductivity measurements in sediment cores obtained under the program of the Geophysics Research Directorate should yield a measure of the heat flow in the Arctic Basin.

A human factors program is under way by personnel of the Aeromedical Laboratory at Ladd Air Force Base.

The Lamont Geological Observatory is carrying on a program at Station A under contract with the Geophysics Research Directorate. Ocean bottom photographs are being taken and cores obtained. Ocean water currents are measured and compared with ice movements. Both refraction and reflection seismic work is being done. The magnetic field is being studied as are the values of gravity.

Fletcher's Ice Island (Drifting Station B)—A meteorological program at Fletcher's Ice Island is being carried out by the U. S. Weather Bureau. It consists essentially of synoptic low altitude observations plus specialized observations similar to those that are being made at Drifting Station A. These include study of radiation, carbon dioxide, precipitation chemistry, and snow crystals. Because of the proximity of meteorologic stations on shore, upper-air weather observations are not made.

The Woods Hole Oceanographic Institution is responsible for an oceanography program at the Ice Island. Bottom cores are being taken, circulation cycles studied, and age determinations made.

Gravity-meter measurements are being made under the cognizance of the University of Wisconsin. There is close coordination at the Ice Island, as at Drifting Station A, between the gravity program and the program of the Geophysics Research Directorate.

The U. S. Army Signal Engineering Laboratories are conducting an ionospheric physics program at the Ice Island and the program is made up primarily of vertical-incidence soundings.

On Fletcher's Ice Island, the Geophysics Research Directorate is carrying out a substantial program similar in some respects to that at Drifting Station A. Primarily it includes aurora investigations, and oceanographic and thermal budget studies. The aurora part of the investigations also makes use of an all-sky camera.

This very brief outline of one segment of the United States IGY Arctic program is designed to give an impression of the nature of the investigations in the Far North, of the many individuals and institutions that are engaged in the program, of the noteworthy cooperation of the Air Force and the other armed services, and of the high degree of coordination that is required.

U. S. Geological Survey, Washington, D. C.